

Transverse-momentum dependence of the J/ψ nuclear modification in $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$

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(Received 4 April 2012; published 14 March 2013)

We present measured J/ψ production rates in $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV over broad ranges of transverse momentum ($p_T = 0\text{--}14$ GeV/ c) and rapidity ($-2.2 < y < 2.2$). We construct the nuclear-modification factor R_{dAu} for these kinematics and as a function of collision centrality (related to impact parameter for the $d + \text{Au}$ collision). We find that the modification is largest for collisions with small impact parameters and observe a suppression ($R_{dAu} < 1$) for $p_T < 4$ GeV/ c at positive rapidities. At negative rapidity we observe a suppression for $p_T < 2$ GeV/ c then an enhancement ($R_{dAu} > 1$) for $p_T > 2$ GeV/ c . The observed enhancement at negative rapidity has implications for the interpretation of the observed modification in heavy-ion collisions at high p_T .

DOI: [10.1103/PhysRevC.87.034904](https://doi.org/10.1103/PhysRevC.87.034904)

PACS number(s): 25.75.Dw

I. INTRODUCTION

Modifications of quarkonia yields when production takes place in a nuclear target, often termed cold-nuclear-matter (CNM) effects, give insight into the production and evolution of $q\bar{q}$ pairs. A number of effects have been predicted to occur in the presence of nuclear matter (for a recent review, see Ref. [1]). These include nuclear breakup, modification of the parton-distribution functions, initial-state parton-energy loss, and, more recently, coherent gluon saturation. Measuring the production rate of quarkonia in a nuclear environment over a broad range of collision energies, and as a function of all kinematic variables, is the best way to disentangle these different mechanisms.

The measurement of J/ψ production rates over broad ranges of rapidity (y) and transverse momentum (p_T) samples a wide range of parton momentum fraction (x) and energy transfer (Q^2), providing constraints on the modification of parton-distribution functions inside nuclei (nPDFs). The deep-inelastic scattering (DIS) data that form the bulk of the current constraints on the nPDF parametrizations are only indirectly related to the gluon distribution. At the Relativistic Heavy Ion Collider (RHIC), the production of J/ψ mesons occurs mainly through gluon fusion. Therefore, our measurements of J/ψ production can provide critical input on the modification of the gluon distribution.

Measuring the p_T distribution of J/ψ production allows access to the Cronin effect [2], which is not accessible by measurements of its rapidity dependence. New data for J/ψ production over a broad range in p_T is necessary to provide guidance for theoretical calculations at high energies.

The CNM effects on J/ψ production have been studied in fixed-target $p + A$ experiments at CERN, FNAL, and DESY [3–9] spanning the center-of-mass energy range $\sqrt{s_{NN}} \approx 17\text{--}42$ GeV. The fixed-target results at midrapidity show an increase in suppression of J/ψ production with decreasing collision energy [7]. This has been interpreted [10] as an increase of the nuclear breakup of the J/ψ through collisions with nuclei. At lower collision energy, the time it takes to cross

the nucleus is long enough for the J/ψ to fully form. The fully formed J/ψ has an increased probability of interacting with other nucleons in the collision, which can cause the breakup of the J/ψ into heavy-meson pairs. At higher collision energies it is likely that the time required for the J/ψ to fully evolve is as long or longer than the crossing time of the collision. This may result in a decrease of the probability for collisions with other nucleons, leading to less suppression of the J/ψ production.

The E866 [8] and HERA-B [9] experiments have measured J/ψ production as a function of p_T in fixed-target $p + A$ experiments. Results are presented in terms of the nuclear-suppression factor, α , which is obtained assuming that the cross section for $p + A$ collisions scales as $\sigma_{pA} = \sigma_{pN} \times A^\alpha$, where σ_{pN} is the proton-nucleon cross section and A is the mass number. Both experiments measure values of α , which are similar across a range of p_T and Feynman- x . The measurements show a suppression of J/ψ production ($\alpha < 1$) for $p_T < 2$ GeV/ c , followed by an enhancement ($\alpha > 1$) for $p_T > 2$ GeV/ c , which is characteristic of multiple scattering of the incident parton [8]. To better understand the J/ψ production mechanism, it is crucial to test these conclusions at the higher energies provided by $d + \text{Au}$ collisions at RHIC.

Measuring, and understanding, the CNM effects on quarkonia production is important for the interpretation of results for J/ψ production in nucleus-nucleus ($A + A$) collisions. In 1986 Matsui and Satz predicted that the suppression of J/ψ production in heavy-ion collisions would be a clear signature of the formation of a quark-gluon plasma [11], because the Debye color screening of the dense medium produced was expected to cause the dissociation of bound states, thereby causing a decrease in the observed production. More recently, suppression of quarkonia production has been observed for a number of states, including the J/ψ and Υ , over a wide range in collision energy [12–15]. However, the interpretation of these results is still unclear. Before the modification owing to the produced medium can be determined, the CNM effects must first be corrected. This has been done at lower energies [12], but accurate data on CNM effects are still absent at the higher energies of RHIC and the LHC.

Here we report new high-precision measurements of the J/ψ production as a function of p_T and collision centrality in $d + \text{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. We also present measurements of the J/ψ R_{dAu} as a function of p_T , rapidity,

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and collision centrality using data for J/ψ production in $p + p$ collisions published in Ref. [16]. PHENIX has previously measured the J/ψ yield in $d + \text{Au}$ collisions [17,18] with data recorded in 2003. The data presented here, recorded in 2008, feature an increase in statistics of 30–50 times over those used in the previously published results, as well as a significant reduction of the systematic uncertainties. The rapidity dependence of J/ψ production in $d + \text{Au}$ collisions from this data set has been previously published in Ref. [19]. This paper presents results for the p_T dependence of the J/ψ yield from the same data set.

II. EXPERIMENTAL APPARATUS AND DATA SETS

The PHENIX detector [20] comprises three separate spectrometers in three pseudorapidity (η) ranges. Two central arms at midrapidity in the nucleon-nucleon center of mass cover $|\eta| < 0.35$ and have an azimuthal coverage (ϕ) of $\pi/2$ rad each, while muon arms at backward/forward rapidity cover $-2.2 < \eta < -1.2$ (Au going direction) and $1.2 < \eta < 2.4$ (d going direction), with full azimuthal coverage.

In the central arms the J/ψ yield is measured via dielectron decays. Tracks from charged particles are reconstructed using the drift chambers and pad chambers. Electron candidates are selected by matching tracks to hits in the ring-imaging Čerenkov (RICH) counters and clusters in the electromagnetic calorimeters (EMCal). In $d + \text{Au}$ collisions, a track is identified as arising from an electron by requiring at least two matching RICH phototube hits within a radius of $3.4 < R[\text{cm}] < 8.4$ with respect to the center defined by the track projection at the RICH. It is also required that the position of the EMCal cluster associated with the track projection match within $\pm 4\sigma$ and that the ratio of the energy deposited in the EMCal cluster to the momentum of the track matches unity within $\pm 2.5\sigma$, where σ characterizes the momentum-dependent widths of the matching distributions. A further cut of 200 MeV/ c on the momentum of the electron is added to reduce the combinatorial background in the J/ψ mass region. This has little effect on the J/ψ yield as the yield of electrons from J/ψ decays observed in data and simulations is negligible below 200 MeV/ c .

At forward and backward rapidity, the J/ψ yield is measured via dimuon decays. Muons are identified by matching tracks measured in cathode-strip chambers, referred to as the muon tracker (MuTr), to hits in alternating planes of Iarocci tubes and steel absorbers, referred to as the muon identifier (MuID). Each muon arm is located behind a thick copper and iron absorber that is meant to stop most hadrons produced during the collisions, so that the detected muons must penetrate 8 to 11 interaction lengths of material.

Beam interactions are selected with a minimum-bias (MB) trigger requiring at least one hit in each of two beam-beam counters (BBCs) located at positive and negative pseudorapidity $3 < |\eta| < 3.9$. The MB selection covers $88\% \pm 4\%$ of the total $d + \text{Au}$ inelastic cross section of 2260 mb [21].

The $d + \text{Au}$ data sample used in this analysis requires the MB trigger to be in coincidence with an additional level-1 trigger. For electrons, this is a single-electron EMCal RICH trigger (ERT), which requires a minimum energy deposited in

any 2×2 group of EMCal towers plus an associated hit in a RICH trigger tile. The possible associations are obtained from a look-up table generated from simulations of single electrons. Two thresholds on the minimum EMCal energy, 600 and 800 MeV, were used, each for roughly half of the data sample. For muons, the level-1 trigger requires two tracks identified as muon candidates. The trigger logic for a muon candidate requires a “road” of fired Iarocci tubes in at least four planes, including the most downstream plane relative to the collision point.

Collisions are required to be within ± 30 cm of the center of the interaction region. Collisions in that range see the full geometric acceptance of the central arms, and this cut also provides a reduction of the systematic uncertainties on the centrality selection needed for the data from the muon arms. The data sets sampled via the level-1 triggers represent analyzed integrated luminosities of 62.7 nb^{-1} (electrons) and 54.0 nb^{-1} (muons) and nucleon-nucleon integrated luminosities of 24.7 and 21.3 pb^{-1} , respectively.

The centrality, which is related to the impact parameter, b , of the $d + \text{Au}$ collision is determined using the total charge deposited in the BBC located at negative rapidity (Au-going direction). The centrality is defined as a percentage of the total charge distribution referenced to the greatest charge, i.e., 0–20% refers to the 20% of the total charge distribution with the greatest charge. On average, the 0–20% centrality corresponds to collisions with the smallest b .

For each centrality bin the mean number of nucleon-nucleon collisions ($\langle N_{\text{coll}} \rangle$) is determined using a Glauber calculation [22] combined with a simulation of the BBC response (as described in Ref. [19]). The resulting $\langle N_{\text{coll}} \rangle$ values for the centrality categories used in this analysis are shown in Table I. The N_{coll} distributions within each centrality bin are shown in Fig. 1. There is a significant overlap between the N_{coll} distributions for different centralities.

Also shown in Table I are the correction factors, c , for all centrality bins, which account for the correlation between the detection of a J/ψ in the final state and an increase in the total charge collected in the BBC [17]. This correlation causes an increase in the MB-trigger efficiency for events which produce a J/ψ and therefore affects the determination of the centrality of a given collision. The correction factors for each centrality bin are obtained within the same Glauber framework as the $\langle N_{\text{coll}} \rangle$ values by assuming that one of the N binary collisions produces a charge in the BBC that is characteristic of a hard-scattering process (the remaining $N - 1$ binary collisions maintain a BBC charge distribution characteristic of soft scattering processes). The increase in

TABLE I. Characterization of the collision centrality for $d + \text{Au}$ collisions along with the correction factor c (see text for details).

Centrality (%)	$\langle N_{\text{coll}} \rangle$	c	$c/\langle N_{\text{coll}} \rangle$
0–20	15.1 ± 1.0	0.94 ± 0.01	0.062 ± 0.003
20–40	10.2 ± 0.7	1.000 ± 0.006	0.098 ± 0.004
40–60	6.6 ± 0.4	1.03 ± 0.02	0.157 ± 0.008
60–88	3.2 ± 0.2	1.03 ± 0.06	0.33 ± 0.02
0–100	7.6 ± 0.4	0.889 ± 0.001	0.117 ± 0.004

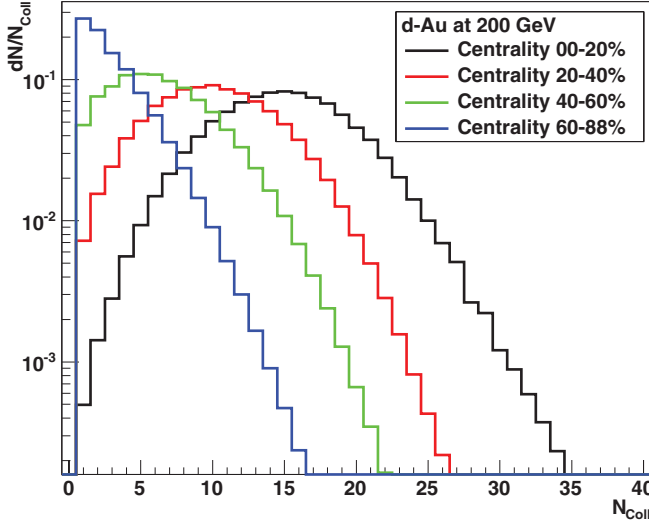


FIG. 1. (Color online) Nucleon-nucleon collision (N_{coll}) distributions for each centrality bin obtained using a Glauber model for $d + \text{Au}$ collisions described in the text.

the BBC charge from a hard process is evaluated using real $p + p$ data by comparing the BBC charge between events with no high- p_T particle ($p_T < 1.5 \text{ GeV}/c$), and those in which a high- p_T pion is reconstructed in the central arms. A value of 1.55 is obtained from this study.

Because both c and $\langle N_{\text{coll}} \rangle$ are calculated in the same Glauber framework their corresponding systematic uncertainties are correlated and partially cancel when taking the ratio $c/\langle N_{\text{coll}} \rangle$, which occurs in the calculation of $R_{d\text{Au}}$. Therefore, the uncertainty in $c/\langle N_{\text{coll}} \rangle$ is investigated separately, and the resulting values and uncertainties are given in the third column of Table I. The correction factor for 0–100% centrality contains an additional factor which corrects for the efficiency of the MB trigger, correcting to 100% of the inelastic $d + \text{Au}$ cross section. This correction is again determined within the Glauber framework using a parametrization of the BBC trigger efficiency given by

$$\epsilon_{\text{BBCLL1}} = 1 - e^{(N/p_0)^{p_1}}, \quad (1)$$

where N is the BBC south arm charge and the parameters p_0 and p_1 are fitted to a comparison of triggered data and Glauber charge distributions.

III. J/ψ ANALYSIS AND RESULTS IN THE MIDRAPIDITY REGION

The procedure for analyzing the $J/\psi \rightarrow e^+e^-$ signal and the results in the central arms are discussed in this section. The extraction of the correlated e^+e^- yield is discussed in Sec. III A. The estimation of the correlated background and losses owing to the radiative tail in the J/ψ mass distribution is discussed in Sec. III B. The estimation of the detector efficiencies is described in Sec. III C. The calculation of the J/ψ invariant yield is detailed in Sec. III D. The $p + p$ baseline used in calculating $R_{d\text{Au}}$ is described in Sec. III E.

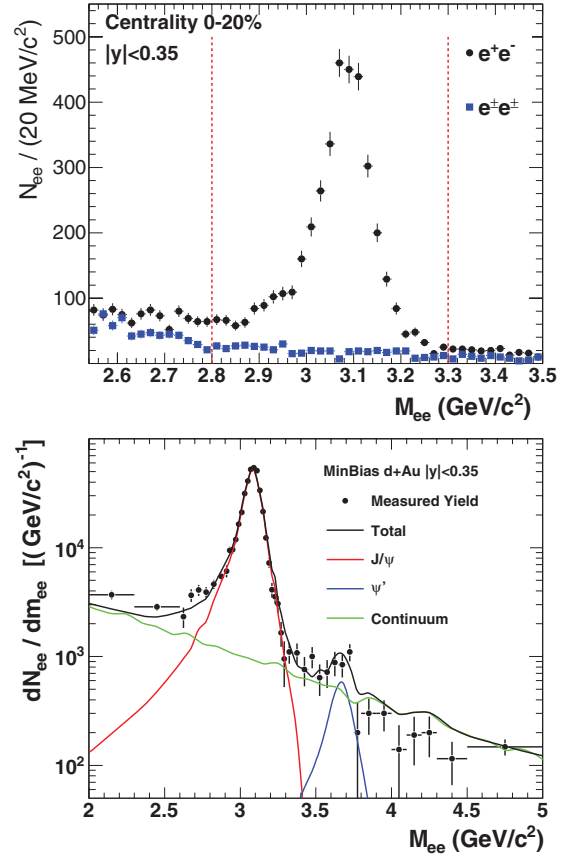


FIG. 2. (Color online) (Top) Invariant mass distribution of unlike-sign (solid circles) and like-sign (solid boxes) dielectron pairs in central $d + \text{Au}$ collisions, integrated over p_T and rapidity. Dashed vertical lines represent the mass range used to determine the correlated e^+e^- yield. (Bottom) Correlated dielectron invariant mass distribution for MB $d + \text{Au}$ collisions. The line shapes are those used to extract the continuum and radiative tail contributions to the correlated e^+e^- yield in the mass range $2.8 < M_{ee} [\text{GeV}/c^2] < 3.3$.

A. Correlated e^+e^- signal extraction

The $J/\psi \rightarrow e^+e^-$ yield is measured using the invariant mass spectrum for all dielectron pairs where at least one of the electrons fired the ERT trigger. This selection is necessary to match the conditions under which the J/ψ trigger efficiency is calculated (see Sec. III C). An example of the dielectron mass spectrum is shown in Fig. 2 for 0–20% central collisions. In a given bin of p_T , rapidity, and collision centrality, the correlated e^+e^- yield ($N_{e^+e^-}$) is determined by counting over a fixed mass window of $2.8 < M_{ee} [\text{GeV}/c^2] < 3.3$ the number of unlike-sign dielectrons, after the subtraction of the like-sign dielectrons, which arise by random association and so are representative of the combinatorial background within the unlike-sign dielectron distribution. This method assumes that the acceptance is the same for e^- and e^+ , which, while untrue at lower masses, is a good assumption in the J/ψ mass range. At higher p_T , where statistical precision is limited, the yield, along with the statistical uncertainties, are derived from Poisson statistics. Assuming both the unlike-sign (foreground) and like-sign (background) are independent, and assuming no

negative signal, the combined distribution

$$P(s) = \sum_{k=0}^{fg} \frac{(bg + fg - k)!}{bg!(fg - k)!} \frac{1}{2} \left(\frac{1}{2}\right)^{bg+fg-k} \frac{s^k e^{-s}}{k!}, \quad (2)$$

represents the probability of a signal (s) given a number of unlike-sign dielectrons (fg) and a number of like-sign dielectrons (bg) (see Ref. [16] for derivation). The mean and standard deviation of Eq. (2) are then used as the yield and uncertainties. A correlated e^+e^- yield in the mass window $2.8 < M_{ee} [\text{GeV}/c^2] < 3.3$ of approximately 8600 is obtained across all p_T and collision centralities.

B. Estimation of the correlated background and losses owing to the radiative tail in the J/ψ mass distribution

When using the like-sign subtraction method there remains a correlated background under the observed J/ψ peak. This background comes mainly from open-heavy-flavor decays and Drell-Yan pairs and must be separated from the J/ψ signal of interest. Counting the dielectron signal only over a fixed mass window also causes an underestimate of the J/ψ yield owing to the fraction of the J/ψ line shape that falls outside the mass window of choice. These two effects are quantified by using simulated particle line shapes fitted to the real data distribution.

To get simulated J/ψ and ψ' line shapes, J/ψ and ψ' mesons with uniform distributions in p_T ($0 < p_T [\text{GeV}/c] < 12$) and rapidity ($|y| < 0.35$) are decayed to e^+e^- and the external radiation effects are evaluated using a GEANT-3-based model of the PHENIX detector (described in Sec. III C). While a uniform distribution in p_T is unrealistic, the J/ψ rapidity distribution is roughly constant within $|y| < 0.35$. When used here, the J/ψ and ψ' line shapes will be compared to p_T integrated data as a function of invariant mass only, with a mass resolution fitted to the data, and therefore the effect of using a uniform p_T distribution is negligible. The line shape for J/ψ radiative decays ($J/\psi \rightarrow e^+e^-\gamma$), also called internal radiation, is based on calculations of the mass distribution from QED [23] convoluted with the detector resolution.

Line shapes for the correlated background from heavy-flavor decays along with Drell-Yan pairs are simulated using PYTHIA [24]. The correlated background from heavy-flavor decays comes from semileptonic decays of correlated $D\bar{D}$ and $B\bar{B}$ (i.e., $D \rightarrow e^+ + X$ and $\bar{D} \rightarrow e^- + X$). The decay electrons from PYTHIA are then run through the same GEANT-3 model of the PHENIX detector that was used for the $J/\psi \rightarrow e^+e^-$ studies to evaluate the external radiation effects. These line shapes are generated assuming $p + p$ collisions, and no corrections for CNM effects (i.e., application of nPDF modifications) are applied to the distributions. We assume that the CNM effects on these distributions are likely small and roughly constant over the narrow mass window used owing to the x values probed. No suppression of heavy-flavor production has been observed in $d + \text{Au}$ collisions, and we assume that any suppression, if it exists, does not significantly effect the overall line shapes.

The line shapes are then fitted to the p_T and collision centrality-integrated invariant mass spectrum over the mass range $2 < M_{ee} [\text{GeV}/c^2] < 8$, where the normalizations on

the J/ψ , ψ' , correlated heavy flavor, and DY are free to vary independently. The best fit in the quarkonium mass region is shown in Fig. 2, where the continuum line shape is the combination of correlated e^+e^- pairs from $D\bar{D}$, $B\bar{B}$, and DY decays, and the J/ψ and ψ' line shapes are the combinations of the line shapes from both internal and external radiation effects. Within the mass window $2.8 < M_{ee} [\text{GeV}/c^2] < 3.3$ the correlated continuum contribution (ϵ_{cont}) is found to be $6.6\% \pm 0.2\%$ and the fraction of the J/ψ line shape contained within the mass window (ϵ_{rad}) to be $94.3\% \pm 0.2\%$, where the uncertainties are derived from the uncertainty in the fit. The disagreement between the fit and the data in the $3.7 < M_{ee} [\text{GeV}/c^2] < 4.5$ mass range is likely attributable to the inability of the $D\bar{D}$ and $B\bar{B}$ line shapes to match the shape of the data at higher mass. However, large changes in the ratio of their contributions have only a small effect on the extracted values of ϵ_{cont} and ϵ_{rad} , and this is accounted for in the quoted uncertainties.

C. Acceptance and efficiency studies

The J/ψ acceptance is investigated using a GEANT-3 [25] based Monte Carlo model of the PHENIX detector. Dead and malfunctioning channels in the detector are masked in both the detector simulation and real data. The accuracy of the simulations is evaluated by comparing simulated single-electron distributions with those from real data. The agreement across the detector and data taking period is determined to be within 3.2%. A conservative estimate, which assumes that the uncertainty is correlated for both electrons in a pair, of $2 \times 3.2\% = 6.4\%$ is assigned as a systematic uncertainty on the J/ψ acceptance based on the quality of the matching between simulations and data.

To determine the J/ψ acceptance, $J/\psi \rightarrow e^+e^-$ decays are simulated with uniform distributions in p_T , rapidity ($|y| < 0.5$), and collision vertex. While distributions uniform in p_T are not realistic, the corrections are made over p_T bins where both the real distribution and the acceptance can be approximated as linear. This assumption, combined with the effect of bin sharing, is taken into account when assigning systematic uncertainties, as described below. The fraction of J/ψ decays that are reconstructed corresponds to the combination of the geometric acceptance and the electron ID efficiency ($A \times \epsilon_{\text{eID}}$). The resulting $A \times \epsilon_{\text{eID}}$ is shown as a function of p_T in Fig. 3. It has an average value of 1.2% in 1 unit of rapidity. The dip in $A \times \epsilon_{\text{eID}}$ at $p_T \approx 3 \text{ GeV}/c$ followed by an increase with p_T marks the transition from the e^+e^- pair at low p_T being produced back to back and being detected one in each of the PHENIX central arms, to the pair at high p_T being produced in a collinear manner and being detected in the same PHENIX central arm. The low point corresponds to the e^+e^- being produced at roughly 90° relative to each other in the lab frame, which, owing to the PHENIX geometry, has the lowest probability for detection.

The electron ID efficiency, which is mainly attributable to track reconstruction cuts used to avoid the misidentification of hadrons as electrons, was cross checked using electrons from π^0 Dalitz decays and γ conversions as described in Ref. [16], and a systematic uncertainty of 1.1% is assigned based on that comparison. The effect of using a flat p_T distribution,

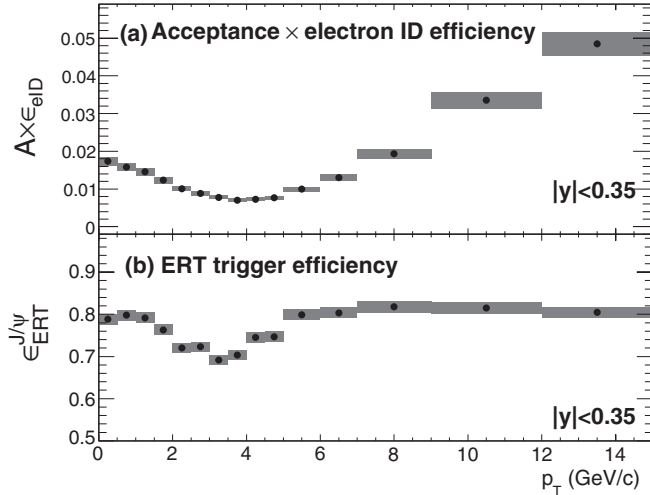


FIG. 3. The J/ψ acceptance \times electron ID efficiency (a) and J/ψ ERT trigger efficiency (b) as a function of p_T for $|y| < 0.35$. The shaded boxes represent the systematic uncertainties.

as well as the effect of momentum smearing on the electrons in simulations, which can cause a J/ψ to be reconstructed into a different p_T bin than the one in which it was generated, was also investigated. A sample of $J/\psi \rightarrow e^+e^-$ decays using realistic y and p_T distributions based on fits to data was generated. The momentum of the decay electrons was randomly smeared based on a measured momentum resolution given by

$$\frac{dp}{p} = 0.72 + 0.75p, \quad (3)$$

which produces a J/ψ mass width that agrees well with data. The ratio of the number of J/ψ 's reconstructed with a p_T in a bin other than the one it was generated in was found to be small for all but the highest p_T bins. An uncertainty of 0.2% was assigned based on the comparison. This finding, along with the approximately linear dependence of the acceptance and yield within the p_T bins used indicates that the effect of using a flat p_T distribution when determining the acceptance should be minimal. A combined uncertainty of 6.5% is assigned to the J/ψ $A \times \epsilon_{\text{ID}}$ by adding the simulation/data matching, eID, and momentum smearing uncertainties in quadrature.

The ERT trigger efficiency is evaluated using simulations of J/ψ decays and parametrizations of the single-electron trigger efficiencies in each trigger tile. A MB data sample of single electrons is used to measure the p_T -dependent efficiency of each 2×2 EMCal trigger tile and each RICH trigger tile independently by calculating the fraction of electrons that fired the trigger tile compared to all those passing through it. The resulting distributions are fitted with an error function for each trigger tile in the EMCal and a constant function for each tile in the RICH. These functions are then used with simulated J/ψ decays to estimate the efficiency of the ERT trigger for triggering on e^+e^- pairs from J/ψ decays ($\epsilon_{\text{ERT}}^{J/\psi}$). The trigger efficiency is evaluated only for simulated J/ψ decays for which both electrons passed an acceptance check, as determined above, to avoid double counting the effect of the acceptance. This procedure was repeated independently for each of the two EMCal trigger thresholds used. The p_T

dependence of $\epsilon_{\text{ERT}}^{J/\psi}$ is shown in Fig. 3, where both ERT trigger thresholds have been combined using the relative luminosities of each data sample. It has an average value of 76%. The dip in $\epsilon_{\text{ERT}}^{J/\psi}$ seen at $p_T \approx 3$ GeV/c is attributable to the kinematics of the J/ψ decays. In that p_T range there is a high probability for the decay electrons to have unbalanced momenta, where one of the electrons will have a momentum below or near the trigger threshold, resulting in a lower probability for triggering on the J/ψ . The effect of the error function used to fit the measured EMCal trigger tile efficiencies is investigated by replacing the error function with a double-Fermi function. This gives an average change in the J/ψ ERT efficiency of 0.31%. The statistical uncertainty in the trigger tile efficiency leads to an uncertainty in the J/ψ ERT efficiency of 1.6%. Summing these uncertainties in quadrature gives a total uncertainty on $\epsilon_{\text{ERT}}^{J/\psi}$ of 1.6%, which is heavily dominated by the uncertainty in the efficiency of each ERT trigger tile.

The track multiplicity dependence of the reconstruction efficiency is negligible (a finding consistent with previous embedding studies in peripheral Cu + Cu [26] with similar multiplicities). A 1% systematic uncertainty was assigned based on studies where simulated J/ψ decays were embedded into real events. This result agrees well with the studies done in Ref. [17], where a slightly larger systematic uncertainty was assigned because of the lower statistical precision of the simulations used.

D. Invariant yield results

The dilepton J/ψ invariant yield in a given rapidity, transverse-momentum, and centrality bin is

$$\frac{B_{ll}}{2\pi p_T} \frac{d^2 N}{dy dp_T} = \frac{1}{2\pi p_T \Delta p_T \Delta y} \frac{c N_{J/\psi}}{N_{\text{EVT}} \epsilon_{\text{tot}}}, \quad (4)$$

where B_{ll} is the $J/\psi \rightarrow l^+l^-$ branching ratio, $N_{J/\psi}$ is the measured J/ψ yield, N_{EVT} is the number of sampled MB events in the given centrality bin, Δy is the width of the rapidity bin, Δp_T is the width of the p_T bin, $\epsilon_{\text{tot}} = A \times \epsilon_{\text{ID}} \times \epsilon_{\text{ERT}}^{J/\psi} \times \epsilon_{\text{rad}}$, and c is the BBC bias correction factor described in Sec. II. At midrapidity $N_{J/\psi} = N_{e^+e^-}(1 - \epsilon_{\text{cont}})$, where ϵ_{cont} is the correlated dielectron continuum contribution in the J/ψ mass range. The 0–100% centrality-integrated J/ψ invariant yield is shown as a function of p_T in Fig. 4 and for four centrality bins in Fig. 5. Here the values shown represent the average over the p_T bin and are plotted at the center of the bin, as this provides the measured information without introducing further systematic uncertainties.

A summary of all the relevant uncertainties at midrapidity is shown in Table II, along with their classification into Type A, B, or C uncertainties. Type A represents uncertainties that are uncorrelated from point to point, Type B represents uncertainties that are correlated from point to point, and Type C represents uncertainties in the overall normalization.

E. $p + p$ baseline

The $p + p$ baseline used to calculate $R_{d\text{Au}}$ is extracted from 2006 data published in Ref. [16]. The integrated

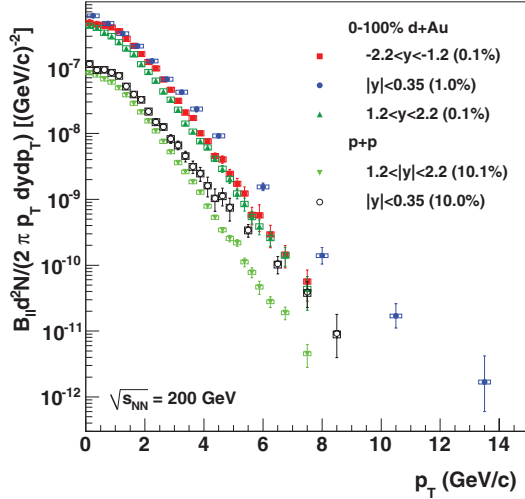


FIG. 4. (Color online) J/ψ invariant yield as a function of p_T for $p + p$ and 0–100% centrality-integrated $d + \text{Au}$ collisions. The Type C systematic uncertainty for each distribution is given as a percentage in the legend. The midrapidity $d + \text{Au}$ and $p + p$ results are discussed in Secs. III D and III E while the forward/backward rapidity results are discussed in Secs. IV C and IV D.

luminosity was $6.2 \pm 0.6 \text{ pb}^{-1}$. The J/ψ polarization has not been measured for $d + \text{Au}$ collisions. In this analysis it is assumed that the polarization is the same for $p + p$ and $d + \text{Au}$ collisions, and therefore the effects of polarization will cancel when forming $R_{d\text{Au}}$. Because the acceptance was calculated here assuming zero polarization, the effect of the J/ψ polarization has been removed from the $p + p$ baseline. The $p + p$ invariant yields as a function of p_T used in this work, shown in Fig. 4, have been obtained from the invariant cross sections published in Ref. [16] using an inelastic cross section of 42 mb.

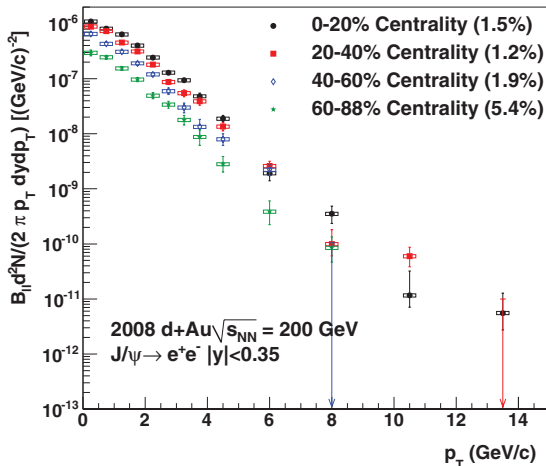


FIG. 5. (Color online) J/ψ invariant yield as a function of p_T for each centrality in the interval $|y| < 0.35$. The Type C systematic uncertainty for each distribution is given as a percentage in the legend.

TABLE II. A summary of the uncertainties in the interval $|y| < 0.35$.

Source	Value (%)	Type
Embedding	1.0	C
ϵ_{rad}	0.2	C
ϵ_{cont}	0.2	C
c (Invariant yield only)	0.1–5.8	C
$c/\langle N_{\text{coll}} \rangle$ ($R_{d\text{Au}}$ only)	3–6	C
$A \times \epsilon_{\text{eID}}$	6.5	B
$\epsilon_{\text{ERT}}^{J/\psi}$	1.6	B
Statistical uncertainty on the measured J/ψ yield		A

IV. J/ψ ANALYSIS AND RESULTS IN THE FORWARD/BACKWARD RAPIDITY REGION

The procedure for analyzing the $J/\psi \rightarrow \mu^+\mu^-$ signal at backward and forward rapidity in the muon arms is discussed in this section. The procedures are similar to those detailed in Refs. [16,27], with only a brief summary presented here, except where there are differences. As in Ref. [16], the rapidity region of the forward muon arm used in the analysis was truncated to $1.2 < y < 2.2$ to match the rapidity coverage of the backward muon arm. The extraction of the raw J/ψ yield is discussed in Sec. IV A. The estimation of the detector efficiencies is described in Sec. IV B. The calculation of the J/ψ invariant yield is detailed in Sec. IV C. The $p + p$ baseline used in calculating $R_{d\text{Au}}$ is described in Sec. IV D.

A. $J/\psi \rightarrow \mu^+\mu^-$ signal extraction

At forward and backward rapidity, the invariant mass distribution is calculated for all unlike-sign dimuons in events that pass the trigger requirements described in Sec. II. The combinatorial background is estimated from the invariant mass distribution formed by pairing unlike-sign muon candidates from different events within bins of similar centrality and collision vertex position. This is done to reduce the statistical uncertainty on the combinatorial background estimation below what is possible by using like-sign pairs from the same event and is needed because the signal to background present at forward/backward rapidity is smaller than at midrapidity. The mixed-event muon pairs are required to have vertices that differ by no more than 3 cm in the beam direction and a centrality that differs by no more than 5%. The mixed-event spectrum is normalized by the factor

$$\alpha = \frac{\sqrt{(N_{\mu^+\mu^+}^{\text{same}})(N_{\mu^-\mu^-}^{\text{same}})}}{\sqrt{(N_{\mu^+\mu^+}^{\text{mixed}})(N_{\mu^-\mu^-}^{\text{mixed}})}}, \quad (5)$$

where $N_{\mu\mu}^{\text{same}}$ and $N_{\mu\mu}^{\text{mixed}}$ are the number of pairs formed from two muons in the same or in mixed events, respectively.

The remaining correlated dimuon mass distribution after the subtraction of the mixed event combinatorial background contains dimuons from J/ψ and ψ' decays, as well as correlated dimuons from heavy-flavor decays and Drell-Yan pairs. Owing to the momentum resolution of the detector there

is no clean discrimination between the J/ψ and ψ' in the mass distribution. However, the ψ' contribution is expected to be negligible in the mass window of interest.

A function consisting of an exponential component combined with two Gaussian distributions, which are used to better reproduce the mass resolution present in the muon arms, is used to fit the dimuon mass distribution, convolved with a function to account for the variation in acceptance over the invariant mass range [16]. The fit function is given by

$$F(M_{\mu\mu}) = \text{Acc}(M_{\mu\mu})[A_{J/\psi}F_{J/\psi}(M_{\mu\mu}) + A_{\text{cont}}e^{-M_{\mu\mu}/b_{\text{cont}}}], \quad (6)$$

where $\text{Acc}(M_{\mu\mu})$ is the mass-dependent acceptance function (see Ref. [16] for examples), $A_{J/\psi}$ is the amplitude of the J/ψ signal, A_{cont} is the amplitude of the continuum contribution, and b_{cont} is the slope of the continuum. $F_{J/\psi}(M_{\mu\mu})$ is the fit function for the J/ψ peak given by

$$F_{J/\psi}(M_{\mu\mu}) = (1 - f_{G2})G(M_{\mu\mu}, M_{J/\psi}, \sigma_{G1}) + f_{G2}G(M_{\mu\mu}, M_{J/\psi} + \delta_M, \sigma_{G2}) \quad (7)$$

$$G(M_{\mu\mu}, M, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(M_{\mu\mu}-M)^2}{2\sigma^2}}, \quad (8)$$

where f_{G2} is the fractional strength of the second Gaussian, σ_{G1} and σ_{G2} are the widths of the first and second Gaussians, respectively, and δ_M is a mass shift introduced in the second Gaussian. f_{G2} , σ_{G1} , σ_{G2} , and δ_M are fixed based on $p + p$ studies [16], while the remaining parameters, $A_{J/\psi}$, A_{cont} , and b_{cont} are free to vary within reasonable limits. The value of the J/ψ mass, $M_{J/\psi}$, is allowed to vary within $\pm 10\%$ of its nominal value. An example of the fitted mass distribution is shown in Fig. 6. Both the J/ψ component of the fit and direct counting after the subtraction of the fitted exponential background are used to evaluate the J/ψ yield. The difference between the two methods is taken as a Type A uncertainty. This uncertainty is typically small ($\approx 2\%$) but can be significantly larger at high p_T , where the statistics are low. Measured J/ψ yields of approximately 42 000 are obtained at both backward and forward rapidity. The slightly larger acceptance at forward rapidity implies a larger J/ψ suppression in this region.

B. Acceptance and efficiency studies

Studies of the response of the muon arm spectrometers to dimuons from J/ψ decays are performed using a tuned GEANT-3-based simulation of the muon arms, coupled with a MuID trigger emulator. The MuID panel-by-panel efficiencies are estimated using reconstructed tracks in real data. Where statistics are limited, the recorded operational history of each channel was used to estimate the efficiency. A systematic uncertainty of 4% on the J/ψ yield is assigned based on the variation of the MuID efficiency. For the MuTr, as is done in $p + p$ [16], charge distributions in each part of the MuTr observed in real data, along with dead channels and their variation with time, are used to give an accurate description of the MuTr efficiency within the detector simulation. A 2% systematic uncertainty on the J/ψ yield is assigned based on the variation of the MuTr efficiency.

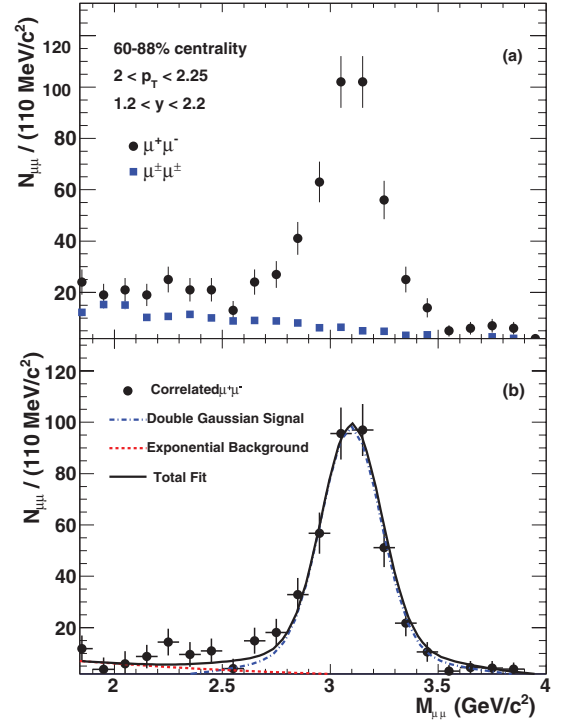


FIG. 6. (Color online) (Top) Invariant mass distribution of unlike-sign (solid circles) and like-sign (solid squares) dimuon pairs for $2 < p_T < 2.25$ GeV/c at forward rapidity and 60–88% central events. (Bottom) Invariant mass distribution of correlated dimuon pairs after the subtraction of the combinatorial background. The solid line represents the fit to the invariant mass distribution, which includes the double Gaussian signal component (dot-dashed line) and exponential background (dotted line).

The evaluation of the J/ψ acceptance \times efficiency ($A \times \epsilon$), which includes the muon trigger efficiency, uses a PYTHIA simulation with several parton distributions as input to account for the unknown underlying rapidity dependence of the J/ψ yield. A 4% systematic uncertainty is assigned based on uncertainties of the parton distributions. A systematic uncertainty of 6.4(7)% on the J/ψ yield is assigned to the backward (forward) rapidity based on differences between the ϕ distributions in data and simulation.

TABLE III. The dominant uncertainties in the interval $1.2 < |y| < 2.2$.

Source	Value (S/N) (%)	Type
c (Invariant yield only)	0.1–5.8	C
$c/\langle N_{\text{coll}} \rangle$ (R_{dAu} only)	3–6	C
MC input distributions	4	B
MuTr efficiency	2	B
MUID efficiency	4	B
Acceptance	6.4/7	B
Fit type	≈ 2	A
Statistical uncertainty on the measured J/ψ yield		A

C. Invariant yield results

The J/ψ invariant yield at backward/forward rapidity is calculated using Eq. (4), where $\epsilon_{\text{tot}} = A \times \epsilon$. A summary of the uncertainties is given in Table III. The backward and forward 0–100% centrality-integrated J/ψ invariant yields are shown as a function of p_T in Fig. 4, while the J/ψ invariant yields are shown as a function of p_T in each centrality bin in Fig. 7.

D. $p + p$ baseline

The $p + p$ baseline used to calculate $R_{d\text{Au}}$ is extracted from a combined analysis of data taken in 2006 and 2008, published in Ref. [16]. The combined integrated luminosity was $9.3 \pm 0.9 \text{ pb}^{-1}$. As discussed in Sec. III E, the effect of the J/ψ polarization on the J/ψ acceptance is removed from the results used here. The J/ψ invariant yield in $p + p$ collisions at forward/backward rapidity used here is also shown as a function of p_T in Fig. 4 for convenience, where we have converted the invariant cross sections published in

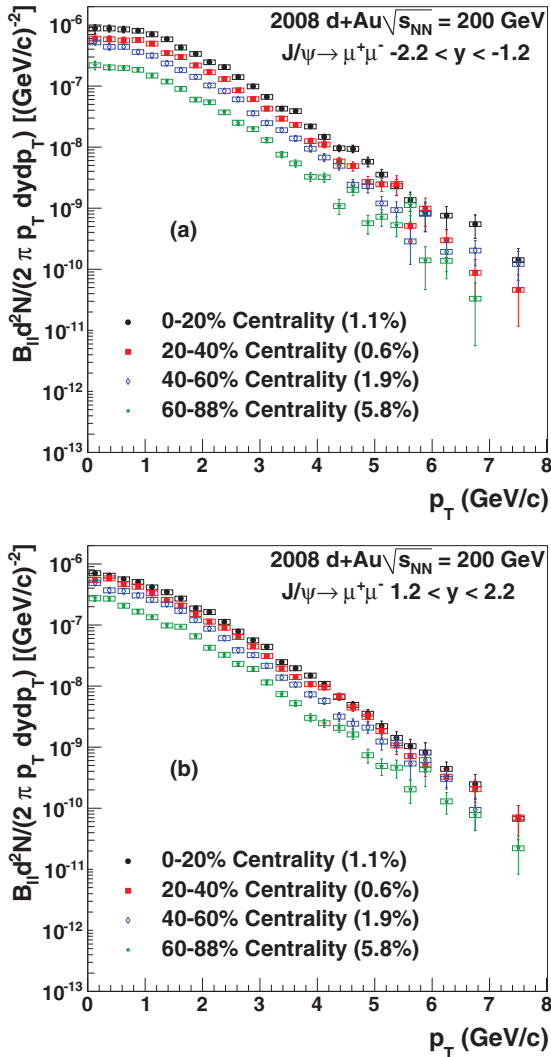


FIG. 7. (Color online) J/ψ invariant yield as a function of p_T for each centrality for (a) $-2.2 < y < -1.2$ and (b) $1.2 < y < 2.2$. The Type C systematic uncertainty for each distribution is given as a percentage in the legend.

TABLE IV. $\langle p_T^2 \rangle$ of J/ψ mesons results for $p + p$ and $d + \text{Au}$ collisions where the first quoted uncertainty corresponds to the Type A uncertainties and the second corresponds to the Type B uncertainties.

System	y range	Centrality (%)	$\langle p_T^2 \rangle$ (GeV^2/c^2)
$p + p$	$1.2 < y < 2.2$		$3.64 \pm 0.03 \pm 0.06$
$p + p$	$ y < 0.35$		$4.46 \pm 0.14 \pm 0.18$
$d + \text{Au}$	$-2.2 < y < -1.2$	0–100	$4.09 \pm 0.06 \pm 0.09$
$d + \text{Au}$	$ y < 0.35$	0–100	$5.10^{+0.12}_{-0.10} \pm 0.11$
$d + \text{Au}$	$1.2 < y < 2.2$	0–100	$4.05 \pm 0.05 \pm 0.10$
$d + \text{Au}$	$-2.2 < y < -1.2$	0–20	$4.22 \pm 0.08 \pm 0.09$
$d + \text{Au}$	$-2.2 < y < -1.2$	20–40	$4.06 \pm 0.08 \pm 0.09$
$d + \text{Au}$	$-2.2 < y < -1.2$	40–60	$4.01 \pm 0.09 \pm 0.09$
$d + \text{Au}$	$-2.2 < y < -1.2$	60–88	$3.92 \pm 0.10 \pm 0.09$
$d + \text{Au}$	$ y < 0.35$	0–20	$5.24^{+0.19}_{-0.16} \pm 0.10$
$d + \text{Au}$	$ y < 0.35$	20–40	$5.27^{+0.22}_{-0.19} \pm 0.12$
$d + \text{Au}$	$ y < 0.35$	40–60	$5.08^{+0.29}_{-0.26} \pm 0.16$
$d + \text{Au}$	$ y < 0.35$	60–88	$4.60^{+0.30}_{-0.24} \pm 0.15$
$d + \text{Au}$	$1.2 < y < 2.2$	0–20	$4.15 \pm 0.06 \pm 0.10$
$d + \text{Au}$	$1.2 < y < 2.2$	20–40	$4.13 \pm 0.07 \pm 0.11$
$d + \text{Au}$	$1.2 < y < 2.2$	40–60	$3.94 \pm 0.07 \pm 0.10$
$d + \text{Au}$	$1.2 < y < 2.2$	60–88	$3.80 \pm 0.08 \pm 0.10$

Ref. [16] into invariant yields using an inelastic cross section of 42 mb.

V. CALCULATION OF $\langle p_T^2 \rangle$

The $\langle p_T^2 \rangle$ is calculated for each of the J/ψ invariant yields presented in Secs. III D and IV C, and the resulting values are shown in Table IV.

Unlike in previous analyses [17], where the $\langle p_T^2 \rangle$ was calculated for $p_T \leq 5 \text{ GeV}/c$ owing to statistical limitations at high p_T , here we have calculated the $\langle p_T^2 \rangle$ over the full p_T range. First, the $\langle p_T^2 \rangle$ was calculated numerically up to the p_T limits of the measured distribution ($\langle p_T^2 \rangle|_{p_T \leq p_T^{\text{max}}}$). The correlated uncertainty was propagated to $\langle p_T^2 \rangle|_{p_T \leq p_T^{\text{max}}}$ by sampling the Type B uncertainty distributions of the first and last p_T point of the invariant yield, and assuming a linear correlation in between. For a more detailed description of this procedure, see Appendix A 3.

To account for the differences in the p_T limits of the various distributions, the $\langle p_T^2 \rangle|_{p_T \leq p_T^{\text{max}}}$ value was corrected to the p_T range from zero to infinity. This was done by fitting the distribution with a modified Kaplan function of the form

$$f(p_T) = p_0 \left[1 - \left(\frac{p_T}{p_l} \right)^2 \right]^{p_2}, \quad (9)$$

where each parameter was free to vary. The ratio

$$k = \frac{\langle p_T^2 \rangle[0, \infty]}{\langle p_T^2 \rangle[0, p_T^{\text{max}}]} \quad (10)$$

was then calculated from the fit and applied to the numerically calculated $\langle p_T^2 \rangle|_{p_T \leq p_T^{\text{max}}}$. In all cases the correction factor

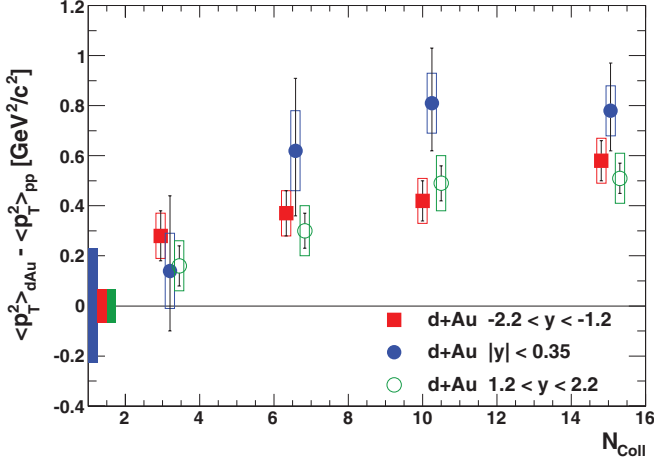


FIG. 8. (Color online) The difference between the J/ψ $\langle p_T^2 \rangle$ in $d + Au$ and $p + p$ collisions as a function of N_{coll} in $d + Au$ collisions. The boxes drawn at $\Delta\langle p_T^2 \rangle = 0$ represent the combined statistical and systematic uncertainties from the $p + p$ calculation.

was small ($k < 1.03$), and an uncertainty in the correction factor based on the fit uncertainty is included in the Type B uncertainties shown in Table IV. For a more detailed description of this procedure, including the fit results and the calculated values of k , see Appendix A.

The $\langle p_T^2 \rangle$ for $p + p$ collisions was previously published in Ref. [16]. However, we report the result here with the effect of the J/ψ polarization on the acceptance removed. The results are in good agreement with those presented in Ref. [16] and are shown in Table IV.

Figure 8 shows $\Delta\langle p_T^2 \rangle = \langle p_T^2 \rangle_{dAu} - \langle p_T^2 \rangle_{pp}$ as a function of N_{coll} . There is a broadening in the p_T distribution with respect to $p + p$, which increases with N_{coll} , and is similar at forward and backward rapidities. We observe a larger increase in the p_T broadening at midrapidity. However, the significance of this observation is limited owing to the relatively large uncertainties present in the data.

VI. THE J/ψ R_{dAu}

To quantify the $d + Au$ CNM effects, the J/ψ R_{dAu} is calculated for a given p_T , y , and centrality bin as

$$R_{dAu}(i) = \frac{c}{\langle N_{coll}(i) \rangle} \frac{d^2 N_{J/\psi}^{d+Au}(i)/dydp_T}{d^2 N_{J/\psi}^{p+p}/dydp_T}, \quad (11)$$

where $d^2 N_{J/\psi}^{d+Au}(i)/dydp_T$ is the $d + Au$ invariant yield for the i th centrality bin, $d^2 N_{J/\psi}^{p+p}/dydp_T$ is the $p + p$ invariant yield for the same p_T and y bin, and $\langle N_{coll}(i) \rangle$ is the average number of binary collisions for the given centrality bin, as listed in Table I.

The 0–100% centrality-integrated J/ψ R_{dAu} as a function of p_T is shown in Fig. 9 for each of the three rapidity regions. The numerical values are tabulated in Appendix B. Figure 9 shows a different behavior for R_{dAu} at backward rapidity ($-2.2 < y < -1.2$) as opposed to mid ($|y| < 0.35$) and forward ($1.2 < y < 2.2$) rapidities. At backward rapidity, the R_{dAu} is suppressed only at the lowest p_T , with a rapid

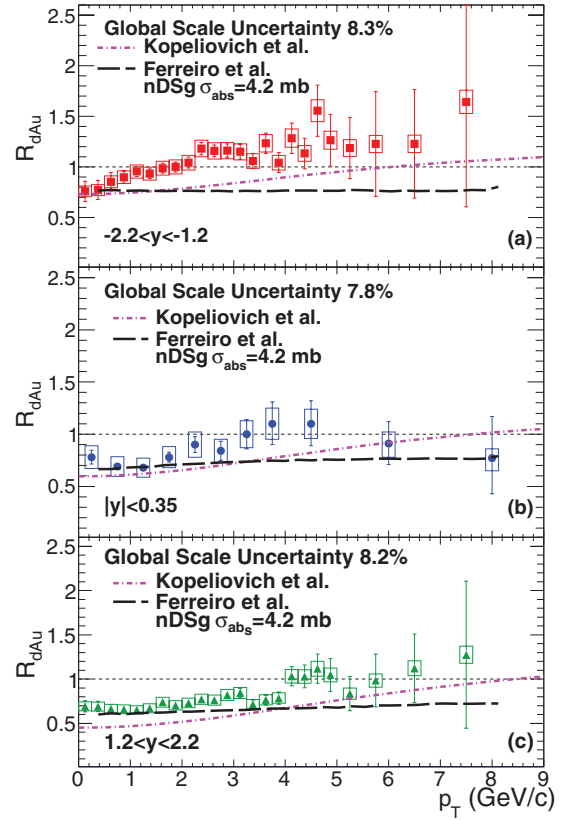


FIG. 9. (Color online) J/ψ nuclear modification factor, R_{dAu} , as a function of p_T for (a) backward rapidity, (b) midrapidity, and (c) forward rapidity 0–100% centrality-integrated $d + Au$ collisions. Curves are model calculations detailed in Sec. VIA.

increase to $R_{dAu} = 1.0$ at $p_T \approx 1.5$ GeV/c. The mid- and forward-rapidity data, however, exhibit a similar level of suppression at the lowest p_T , but a much more gradual increase in R_{dAu} with p_T , increasing to $R_{dAu} = 1.0$ only at $p_T \approx 4.0$ GeV/c. Figure 10 shows the same 0–100% R_{dAu} vs p_T at all rapidities overlaid. It is striking that the shape and absolute scale for the mid- and forward-rapidity data are nearly consistent across the entire p_T range of the data.

Owing to the statistical limitations of the data at high p_T , it is unclear from Fig. 9 whether the R_{dAu} increases significantly above one. To investigate the high- p_T behavior of the R_{dAu} at each rapidity, the average R_{dAu} was calculated for $p_T > 4$ GeV/c by fitting each distribution with a constant. The results are shown in Table V along with the fit uncertainties, which take into account only the Type A uncertainties on the

TABLE V. The average 0–100% R_{dAu} for $p_T > 4$ GeV/c where the first quoted uncertainty corresponds to the fit uncertainty and the second corresponds to the combined Type B and C systematic uncertainties.

Rapidity	R_{dAu} ($p_T > 4$ GeV/c)
$-2.2 < y < -1.2$	$1.27 \pm 0.06 \pm 0.11$
$ y < 0.35$	$0.97 \pm 0.14 \pm 0.16$
$1.2 < y < 2.2$	$1.03 \pm 0.06 \pm 0.11$

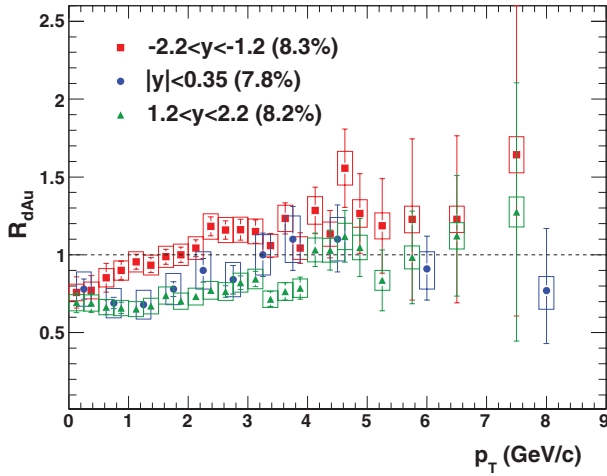


FIG. 10. (Color online) J/ψ R_{dAu} , as a function of p_T for 0–100% centrality-integrated $d + Au$ collisions in all three rapidity intervals. The Type C systematic uncertainty for each distribution is given as a percentage in the legend.

data. Because the Type B uncertainties are roughly consistent in the fit range, we have chosen here to add the average Type B uncertainty for $p_T > 4$ GeV/c in quadrature with the Type C uncertainty. We find that at mid- and forward rapidity the average R_{dAu} for $p_T > 4$ GeV/c is consistent with 1.0, while at backward rapidity the average R_{dAu} is greater than 1.0.

The production of a J/ψ at forward rapidity in $A + A$ collisions involves a low- x gluon colliding with a high- x gluon. The symmetry owing to identical colliding nuclei results, essentially, in the folding of the forward and backward rapidity R_{dAu} . The production of a J/ψ at midrapidity results, essentially, in the folding of the midrapidity R_{dAu} with itself. This picture is simplistic and leaves out many details, but it gives some expectation for the result of the modification of J/ψ production in $A + A$ collisions owing to CNM effects. If we extrapolate the observed behavior of R_{dAu} to the modification of J/ψ 's produced at forward rapidity in $A + A$ collisions, we would expect a R_{AA} contribution from CNM effects to be similar to, or greater than, 1.0 at high p_T and a modification similar to 1.0 at midrapidity. The observation at midrapidity of a J/ψ R_{AA} in Cu + Cu collisions that exceeds, but is consistent with, 1.0 at high p_T [28] may therefore be largely accounted for by the contribution from CNM effects. Further work is needed to understand the detailed propagation of measured results in $d + Au$ collisions to an expected CNM contribution in $A + A$ collisions before this can be fully understood.

Figures 11–13 show R_{dAu} vs p_T in four centrality bins for backward rapidity, midrapidity, and forward rapidity, respectively. The numerical values are tabulated in Appendix B. For peripheral collisions the R_{dAu} remains consistent with 1.0 within statistical and systematic uncertainties across all p_T in all rapidity regions.

A. Comparison with model predictions

As mentioned previously, various models have been suggested to describe the CNM effects on J/ψ production.

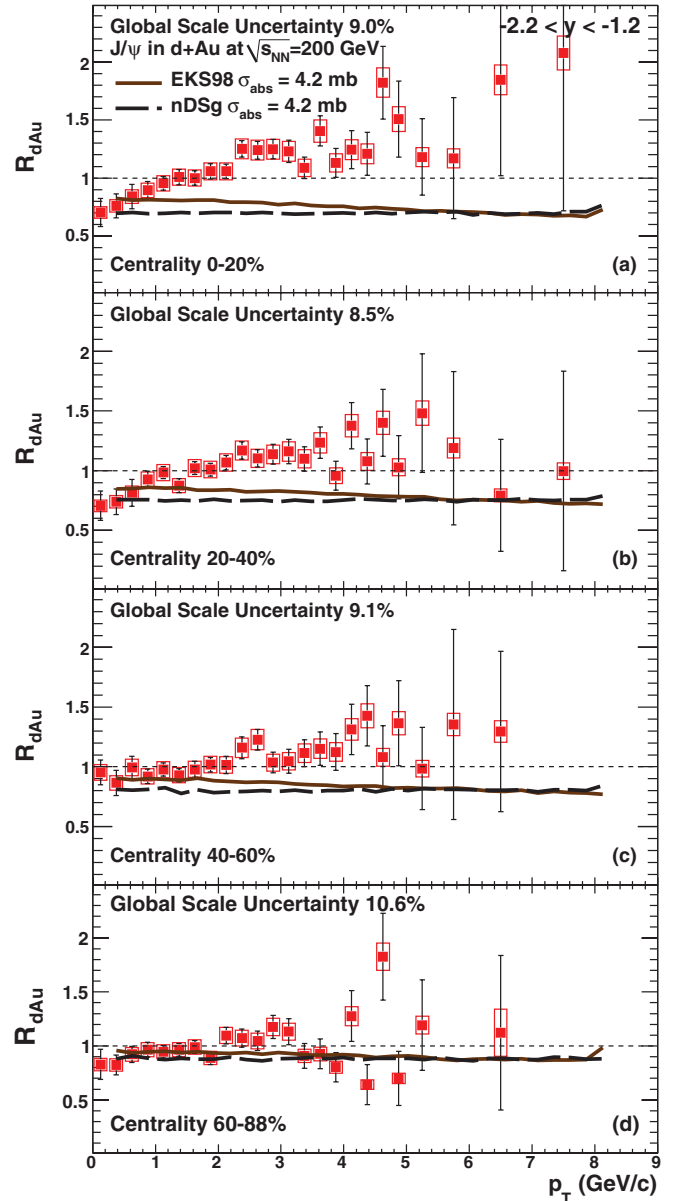


FIG. 11. (Color online) $J/\psi \rightarrow \mu^+ \mu^-$ R_{dAu} , as a function of p_T for (a) central, (b) midcentral, (c) midperipheral, and (d) peripheral events in the interval $-2.2 < y < -1.2$. The 60–88% R_{dAu} point at $p_T = 5.75$ GeV/c has been left off the plot, because it is above the plotted range and has very large uncertainties; however, it is included in the last Table of Appendix B. Curves are calculations by Ferreiro *et al.* [29] discussed in the text.

The models that will be discussed here include a combination of physical effects such as shadowing, nuclear breakup, and the Cronin effect.

Shadowing, the modification of the parton distributions within a nucleus, is calculated using parametrizations of DIS data in the form of nuclear modified parton distribution functions (nPDF's). There are a number of nPDF sets available, including deFlorian-Sassot (nDSg) [30], Eskola-Kolhinen-Salgado (EKS98) [31], and Eskola-Paukkunen-Salgado (EPS09) [32], which provide the kinematic dependence of the modification based on different parametrizations

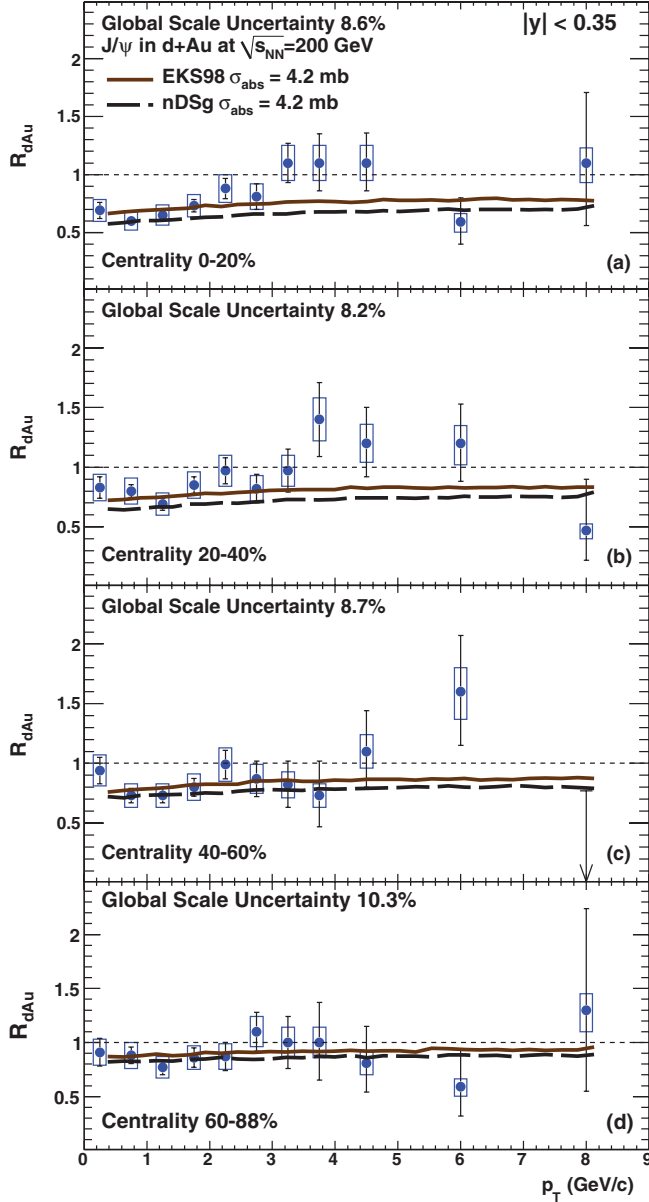


FIG. 12. (Color online) $J/\psi \rightarrow e^+e^-$ R_{dAu} , as a function of p_T for (a) central, (b) midcentral, (c) midperipheral, and (d) peripheral events in the interval $|y| < 0.35$. Curves are calculations by Ferreiro *et al.* [29] discussed in the text.

of the available data. For J/ψ production in $d + Au$ collisions the relevant distributions are those providing the modification of the gluon distribution within a Au nucleus, as J/ψ 's are produced primarily through gluon fusion at $\sqrt{s_{NN}} = 200$ GeV. The nPDF's provide modifications as a function of parton momentum fraction (x) and energy transfer (Q^2). Knowledge of the J/ψ production kinematics is then needed to produce a modification to J/ψ production in $d + Au$ collisions. For J/ψ production at backward rapidity and $0 < p_T < 8$ GeV/c, a range of $0.051 < x < 0.39$ in the Au nucleus is probed, assuming simple $2 \rightarrow 1$ kinematics. While $2 \rightarrow 1$ kinematics are inadequate to describe the production of a J/ψ with

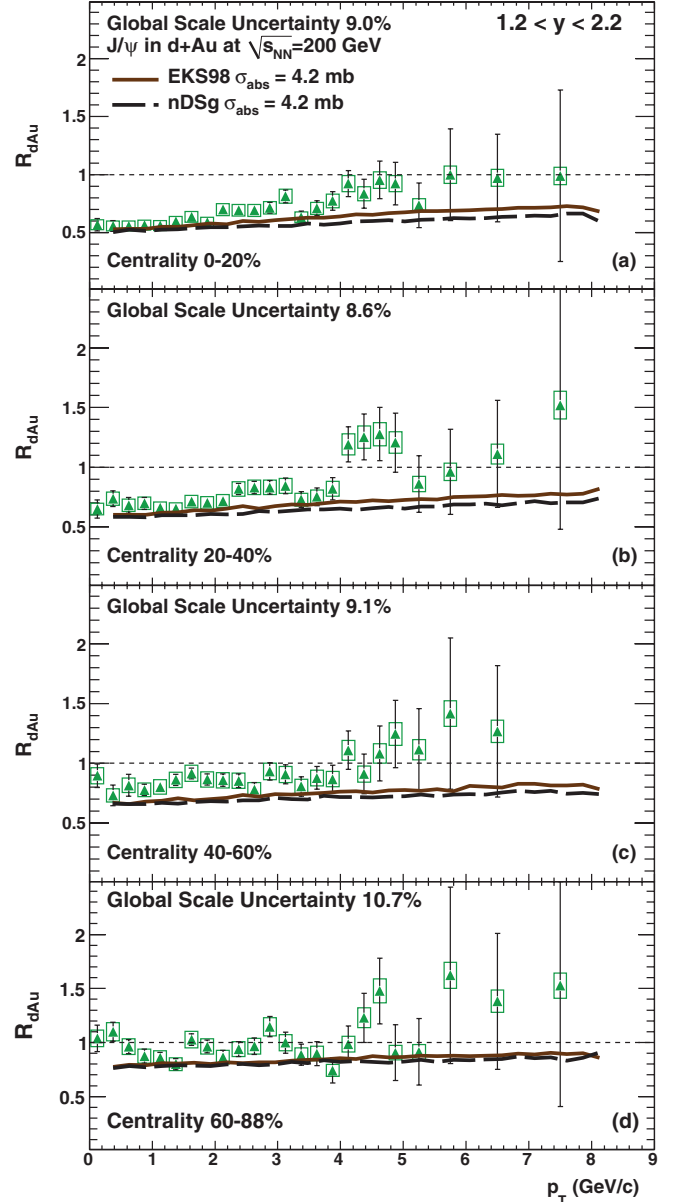


FIG. 13. (Color online) $J/\psi \rightarrow \mu^+\mu^-$ R_{dAu} , as a function of p_T for (a) central, (b) midcentral, (c) midperipheral, and (d) peripheral events in the interval $1.2 < y < 2.2$. Curves are calculations by Ferreiro *et al.* [29] discussed in the text.

nonzero p_T , they are used here to provide a simple estimation of the x and Q^2 ranges covered. With the same assumption, midrapidity covers $0.0094 < x < 0.071$ and forward rapidity covers $0.0017 < x < 0.013$. A range of $10 < Q^2 [\text{GeV}^2/c^2] < 74$ is probed at each rapidity under the same assumptions. The data thus provide a strong constraint to shadowing models over a wide range of x and Q^2 .

Nuclear breakup is the dissociation of $c\bar{c}$ pairs that would have formed J/ψ 's through collisions with nucleons. Little theoretical guidance currently exists for this, owing to the many complications and competing effects involved in J/ψ production in $p(d) + A$ collisions. Often this effect is modeled by a simple "effective" cross section, which remains constant

with p_T ; however, there are a number of models, including a dynamic breakup cross section [33] that changes based on the kinematics of the produced J/ψ .

The broadening of the p_T distribution, termed the Cronin effect [2], is typically attributed to multiple elastic scattering of the incoming parton before the hard collision that produces the J/ψ . This modifies the p_T dependence of the J/ψ production by adding p_T vectorially to the incoming parton. This generally causes a decrease in J/ψ production at low p_T and a compensating increase at higher p_T ($p_T \approx 5\text{--}10$ GeV/c), which eventually falls off at yet higher p_T ($p_T \approx 10$ GeV/c).

The first set of model calculations that we discuss is by Kopeliovich *et al.* [34,35], where the effects on a $c\bar{c}$ dipole propagating through a nucleus are calculated. The J/ψ production is calculated based on $2 \rightarrow 1$ kinematics,

$$x = \frac{\sqrt{\langle M_{c\bar{c}}^2 \rangle + \langle p_T^2 \rangle}}{\sqrt{s}} e^{-y}, \quad (12)$$

where $\langle M_{c\bar{c}}^2 \rangle = 2M_{J/\psi}^2$ is fixed based on the $c\bar{c}$ invariant mass distribution predicted by the color singlet model. The calculation includes shadowing, taken from the nDSg nPDF set, as well as nuclear breakup and the Cronin effect. The nuclear breakup is calculated using a parametrization of the dipole cross section fitted to measurements of the proton structure function at HERA [33], yielding a breakup cross section that is dependent on the p_T and rapidity of the J/ψ . The results from this calculation are shown for the 0–100% R_{dAu} at all rapidities in Fig. 9 as the dot-dashed curves. This is a parameter free calculation, with no overall normalization or fits to the data presented here. The shape of the p_T dependence is in good agreement with the data at mid- and forward rapidity, but the theory shows a greater overall level of suppression than is seen in the data. At backward rapidity, there is a disagreement with the shape of the p_T distribution. While the theory predicts a similar p_T shape at all rapidities, the data show a much faster rise in R_{dAu} with increasing p_T at backward rapidity. It is also worth noting, as shown in Ref. [36], that this model cannot simultaneously describe the rapidity dependence of the PHENIX R_{dAu} and R_{CP} for J/ψ production, where R_{CP} is the ratio of R_{dAu} in central collisions to that in peripheral collisions. This indicates that the model may not have an accurate description of the geometric dependence of the modification.

A second set of model calculations, performed by Ferreiro *et al.* [29,37], is shown in Fig. 9. This model uses a Monte Carlo approach within a Glauber model of $d + Au$ collisions. The J/ψ production is calculated using the color singlet model, $g + g \rightarrow J/\psi + g$, where the majority of the J/ψ p_T is balanced by the emission of a hard gluon in the final state. Thus, it involves $2 \rightarrow 2$ processes rather than $2 \rightarrow 1$ processes, where the J/ψ p_T comes entirely from the transverse momentum carried by the colliding gluons. The J/ψ production is modified in $d + Au$ collisions by shadowing effects parametrized using various nPDF sets. The calculations shown in Fig. 9 utilize the nDSg nPDF set. Similar calculations using the EKS98 and EPS08 [38] nPDF sets can be found in Ref. [29]. Nuclear breakup of the J/ψ is taken

into account through the use of an effective, p_T -independent, absorption cross section of 4.2 mb. Results using $\sigma_{abs} = 0, 2.6$, and 6 mb can also be found in Ref. [29]. We have chosen to highlight only $\sigma_{abs} = 4.2$ mb here as it reproduces the rapidity dependence of the 60–88% R_{dAu} , where shadowing corrections are expected to be small reasonably well [29]. The results of this calculation, shown in Fig. 9 for 0–100% R_{dAu} at all rapidities, shows reasonable agreement with the overall level of modification seen at low p_T in the data at mid- and forward rapidities, while predicting a flatter distribution with increasing p_T than is seen in the data. The shape of the distribution at backward rapidity is markedly different than the data. While the data rapidly increase to $R_{dAu} \approx 1$ at low p_T , the calculation shows a R_{dAu} that is essentially constant with increasing p_T .

When comparing the two sets of model calculations in Fig. 9 the calculations from Kopeliovich *et al.* [34,35] have a different shape than the calculations by Ferreiro *et al.* [29,37]. Both sets of calculations utilize the nDSg nPDF set, suggesting that there should be a common contribution from shadowing. However, the J/ψ production kinematics are calculated differently, which will lead to some difference in the shadowing contribution. The calculations from Kopeliovich *et al.* include the Cronin effect, which provides a decrease in J/ψ production at low p_T and an increase at higher p_T , creating an R_{dAu} that exhibits less suppression at high p_T than at low p_T . The calculations from Ferreiro *et al.* do not include the Cronin effect, and therefore the p_T shape of R_{dAu} should be dominated by the effect of shadowing, and therefore by the choice of nPDF set.

The spatial dependence of the shadowing has been taken into account in Ref. [29], where it is assumed that the shadowing is proportional to the local nuclear density. This assumption allows for calculation of the R_{dAu} vs p_T in different centrality bins. The results of the calculation in the four PHENIX centrality bins are shown in Figs. 11–13 for backward, mid-, and forward rapidity, respectively. Here we have chosen to include calculations using the EKS98 nPDF set along with those using the nDSg nPDF set as this will provide a direct comparison between the effects owing to different nPDF sets, because the J/ψ production kinematics and σ_{abs} values are identical between the two calculations. At mid- and forward rapidity the calculations are similar to each other and show reasonable agreement with the R_{dAu} distributions within the current statistical and systematic uncertainties, although the calculation appears to predict a slightly larger average suppression for peripheral collisions at forward rapidity than is seen in the data. This could be attributable to the value of σ_{abs} used at forward rapidity, as the value of 4.2 mb was chosen by eye rather than fitted to the data, and it may not be independent of y .

At backward rapidity, the calculations are in disagreement with the data for all but the most peripheral collisions, where both the calculations and the data show an R_{dAu} consistent with 1.0 at all p_T . While the calculations at backward rapidity using the nDSg nPDF set are roughly constant with p_T for each centrality, the calculations using the EKS98 nPDF set show increasing suppression of R_{dAu} with increasing p_T for central and midcentral collisions. The data show the opposite trend. At backward rapidity and low p_T (Bjorken $x \approx 0.1$

for the parton in the Au nucleus), production occurs in the antishadowing region, while at high p_T ($x \approx 0.3$) production begins to move towards what is termed the EMC [39] region. In 1986, a suppression of the quark distributions within nuclei was discovered in the range $0.35 < x < 0.7$ by the European Muon Collaboration (EMC) [39] in DIS. While there is still a debate about the source of this suppression in the quark distributions, no direct evidence of an EMC effect has yet been reported in the gluon distributions. Few constraints exist in this region, and there is large disagreement in the modification of the gluon density between different nPDF's. The nDSg nPDF set includes no suppression in the EMC region, and only a small antishadowing effect, while the EKS98 nPDF exhibits a suppression in the EMC region similar to that observed in the quark distributions, and a larger antishadowing effect (see Ref. [32] for a comparison of nPDF sets). The larger antishadowing combined with the inclusion of an EMC effect in the EKS98 nPDF set cause a decrease in the calculated R_{dAu} as p_T (and correspondingly, x) increases. The lack of a strong antishadowing effect combined with the absence of an EMC effect in the nDSg nPDF causes the calculation of R_{dAu} to remain roughly constant with increasing p_T .

In Ref. [40] the authors infer from measurements of Υ production at RHIC that a strong EMC effect must be present to explain the observed modification. Depending on the mapping of the J/ψ y and p_T to x , which is model dependent, the high- p_T data at backward rapidity may allow us to probe this region. The large uncertainties present in the high- p_T R_{dAu} , along with complications from competing physics effects in this region, however, prevent any strong conclusions from being drawn at this time.

A third set of model calculations by Sharma and Vitev [41] is compared with the midrapidity 0–100% centrality-integrated R_{dAu} in Fig. 14. This model describes J/ψ production using nonrelativistic quantum chromodynamics (NRQCD). The effect of nuclear shadowing is calculated using EKS98 in the EMC region ($x > 0.25$), while for lower

values, power suppressed coherent final-state scattering leads to a modification of parton x [42]. Initial-state energy loss, which accounts for the radiative energy loss of the incoming particles through multiple interactions with the target nucleus is included. This effect reduces the energy of the incoming parton, so, to achieve the same final-state kinematics the parton must have a greater momentum and therefore a larger value of x . This effectively shifts the portion of the gluon distribution sampled to higher x . The solid curve in Fig. 14 shows the full calculation including the Cronin effect. The dashed curve in Fig. 14 is the same calculation without the Cronin effect. This comparison gives a direct indication of the contribution from the Cronin effect, which is evidently overpredicted when compared to the data. The results presented here will hopefully provide a much needed constraint on the Cronin effect at RHIC energies. The calculation including the Cronin effect indicates an R_{dAu} that decreases at higher p_T . This is consistent with the data; however, the current statistical and systematic uncertainties make determining the precise trend of R_{dAu} difficult at high p_T . Better data with a larger p_T coverage are needed to determine the J/ψ modification at higher p_T .

VII. SUMMARY AND CONCLUSIONS

We have measured the J/ψ invariant yield and R_{dAu} , as a function of p_T over three rapidity ranges in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV using the PHENIX detector. These measurements provide a large improvement in statistical precision and p_T reach over the previously published PHENIX $d + Au$ results [17,18] and are the first measurements of the centrality dependence of the J/ψ p_T distribution in $d + Au$ collisions by PHENIX. The $\Delta\langle p_T^2 \rangle$ values determined from the data show a marked increase with N_{coll} that is similar at all rapidities.

The R_{dAu} vs p_T displays similar behavior at mid- and forward rapidity, showing suppression at low p_T with a gradual increase to a value consistent with 1.0. The R_{dAu} at backward rapidity has a different distribution with p_T , showing a more rapid increase from suppression to a value of 1.0 and transitioning to $R_{dAu} > 1.0$ above 2 GeV/c. These trends are greater for central collisions, while the peripheral collisions show R_{dAu} consistent with 1.0 across all rapidities.

We find an average R_{dAu} for $p_T > 4$ GeV/c of $1.27 \pm 0.06 \pm 0.11$ at backward rapidity, and an R_{dAu} consistent with 1.0 at mid- and forward rapidity. This implies a CNM contribution in $A + A$ collisions that is likely consistent with 1.0 at high p_T across all rapidity. This could potentially accounts for the reported lack of suppression in R_{AA} at high p_T [28]. However, more data and further work to understand the propagation of R_{dAu} to R_{AA} is needed to confirm this.

A comparison of the measured R_{dAu} with three types of theoretical calculations was shown. The parameter-independent dipole model of J/ψ production in $p + A$ collisions agrees well with the shape of the data at mid- and forward rapidities, while the shape of the predicted p_T dependence is different from the data at backward rapidity. However, the suppression is overpredicted at all rapidities. The second model uses $2 \rightarrow 2$ J/ψ production kinematics coupled with shadowing taken from both EKS98 and nDSg nPDF sets

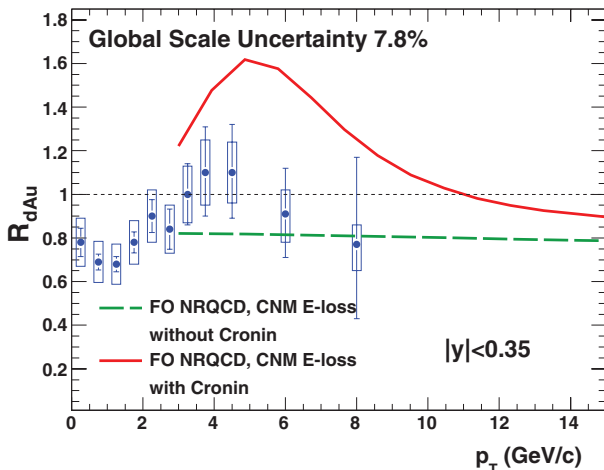


FIG. 14. (Color online) J/ψ R_{dAu} , as a function of p_T for midrapidity 0–100% centrality-integrated $d + Au$ collisions. The curves are NRQCD calculations from Ref. [41] described in the text.

as well as an effective absorption cross section of 4.2 mb. The calculations with both EKS98 and nDSg show good agreement with the data at midrapidity in each centrality bin, as well as the centrality-integrated case. At forward rapidity, the shape of the distribution is in reasonable agreement with the data, while the overall level of suppression seems to be greater in the model calculations than the data. At backward rapidity, the model calculations using both EKS98 and nDSG nPDF sets are in strong disagreement with the data. At backward rapidity, calculations using the nDSg nPDF set show a suppression that is constant with p_T , while those using the EKS98 nPDF set predict an increase of suppression with increasing p_T . The data show the opposite trend. The third model, an NRQCD calculation of high p_T J/ψ production, show a Cronin effect, which although generally consistent with the data, is significantly larger than observed in the data, and a suppression at high p_T that cannot be confirmed by the present data owing to the large uncertainties at high p_T and the limited p_T reach of the current data.

In summary, the data presented here cover a large range in x and Q^2 , providing a further constraint on the modification of the gluon distribution in nuclei, as well as providing constraints on the size of the Cronin effect on J/ψ production at RHIC.

ACKNOWLEDGMENTS

We thank the staff of the Collider-Accelerator and Physics Departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We thank Jean-Philippe Lansberg, Nicolas Matagne, Boris Kopeliovich, Ivan Vitev, and Rishi Sharma for useful discussions and theoretical calculations. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean

of the College of Arts and Sciences, Vanderbilt University (USA); Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan); Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil); Natural Science Foundation of China (People's Republic of China); Ministry of Education, Youth and Sports (Czech Republic); Centre National de la Recherche Scientifique, Commissariat à l'Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France); Ministry of Industry, Science and Technologies, Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Germany); Hungarian National Science Fund, OTKA (Hungary); Department of Atomic Energy and Department of Science and Technology (India); Israel Science Foundation (Israel); National Research Foundation and WCU program of the Ministry Education Science and Technology (Korea); Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic Energy (Russia); VR and the Wallenberg Foundation (Sweden); the US Civilian Research and Development Foundation for the Independent States of the Former Soviet Union; the US-Hungarian Fulbright Foundation for Educational Exchange; and the US-Israel Binational Science Foundation.

APPENDIX A: DETAILS ON THE CALCULATION OF $\langle p_T^2 \rangle$

1. Fitting the J/ψ invariant yields

The J/ψ invariant yields as a function of p_T were fitted with a modified Kaplan function of the form

$$f(p_T) = p_0 \left[1 - \left(\frac{p_T}{p_l} \right)^2 \right]^{p_2}. \quad (\text{A1})$$

The data points were compared to the integral of the function over the p_T bin when calculating the χ^2 . The fit results, along with the ratio of the data to the fit are shown in Fig. 15 for $p + p$ collisions and Fig. 16 for 0–100% centrality-integrated $d + \text{Au}$ collisions. The fit results for each centrality bin are shown in Figs. 17–19 for backward, mid-, and forward rapidities, respectively.

2. Calculating the correction factor k

To account for the fact that the experimental upper p_T limits on the J/ψ invariant yield distributions vary with rapidity and centrality, a correction factor was calculated using the fits described in Appendix A 1. The ratio

$$k = \frac{\langle p_T^2 \rangle [0, \infty]}{\langle p_T^2 \rangle [0, p_T^{\text{max}}]} \quad (\text{A2})$$

was calculated from the fit and applied to the numerically calculated $\langle p_T^2 \rangle|_{p_T \leq p_T^{\text{max}}}$. The correction factors are shown in Table VI, and are in all cases small ($k < 1.03$). The uncertainty on k is derived from the fit uncertainty by varying the data points within their statistical uncertainties, refitting, and thereby finding the variation in k .

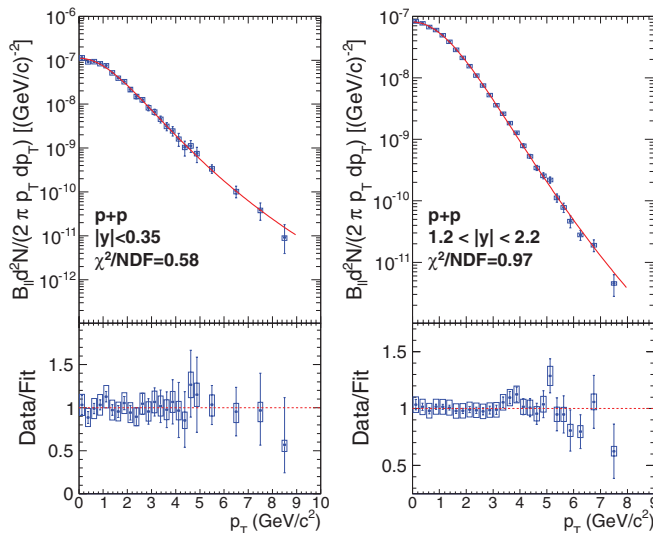


FIG. 15. (Color online) Results of modified Kaplan fits to midrapidity $p + p$ (left) and forward-rapidity $p + p$ (right).

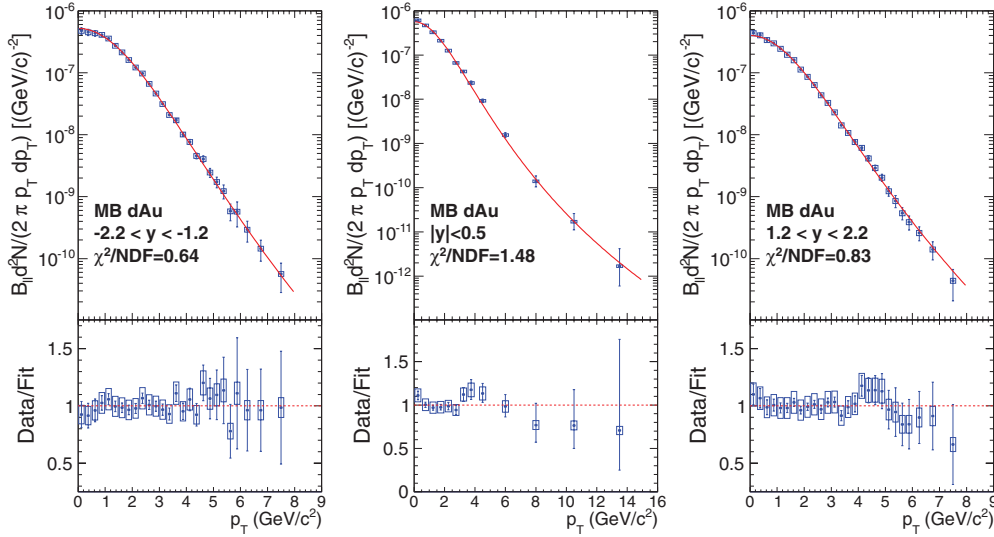


FIG. 16. (Color online) Results of modified Kaplan fits to backward-rapidity 0–100% $d + \text{Au}$ (left), midrapidity 0–100% $d + \text{Au}$ (center), and forward-rapidity 0–100% $d + \text{Au}$ (right).

3. Propagating the Type B uncertainties to $\langle p_T^2 \rangle$

When propagating the Type B systematic uncertainties on the J/ψ invariant yields to the calculated $\langle p_T^2 \rangle$ values, the Type B uncertainties are assumed to be normally distributed. With this assumption we independently sample the uncertainty distribution of the first and the last data point of the p_T distribution. We then assume the Type B uncertainties are

linearly correlated between these two values. The resulting distribution of the $\langle p_T^2 \rangle$ values that arises from this procedure gives an estimate of the effect of the Type B uncertainties on the value of $\langle p_T^2 \rangle$.

The Type C systematic uncertainties on the J/ψ invariant yields do not affect the calculation of $\langle p_T^2 \rangle$. The Type C uncertainties are a global uncertainty, which cancels in the calculation.

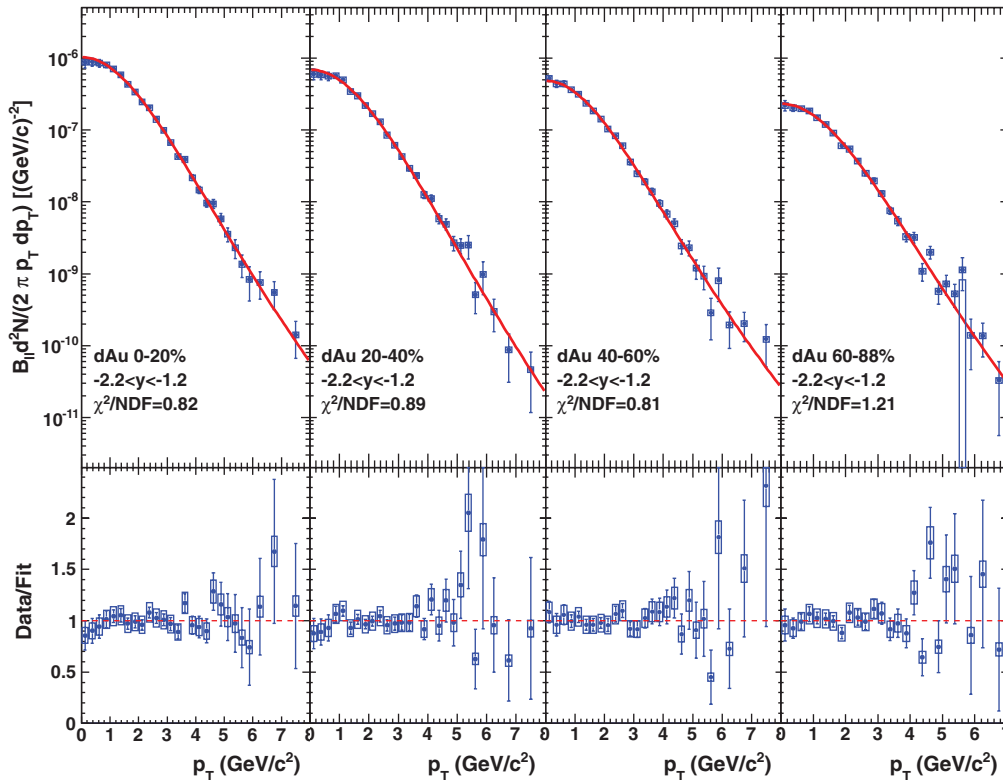


FIG. 17. (Color online) Results of modified Kaplan fits to backward-rapidity $d + \text{Au}$ collisions for each centrality.

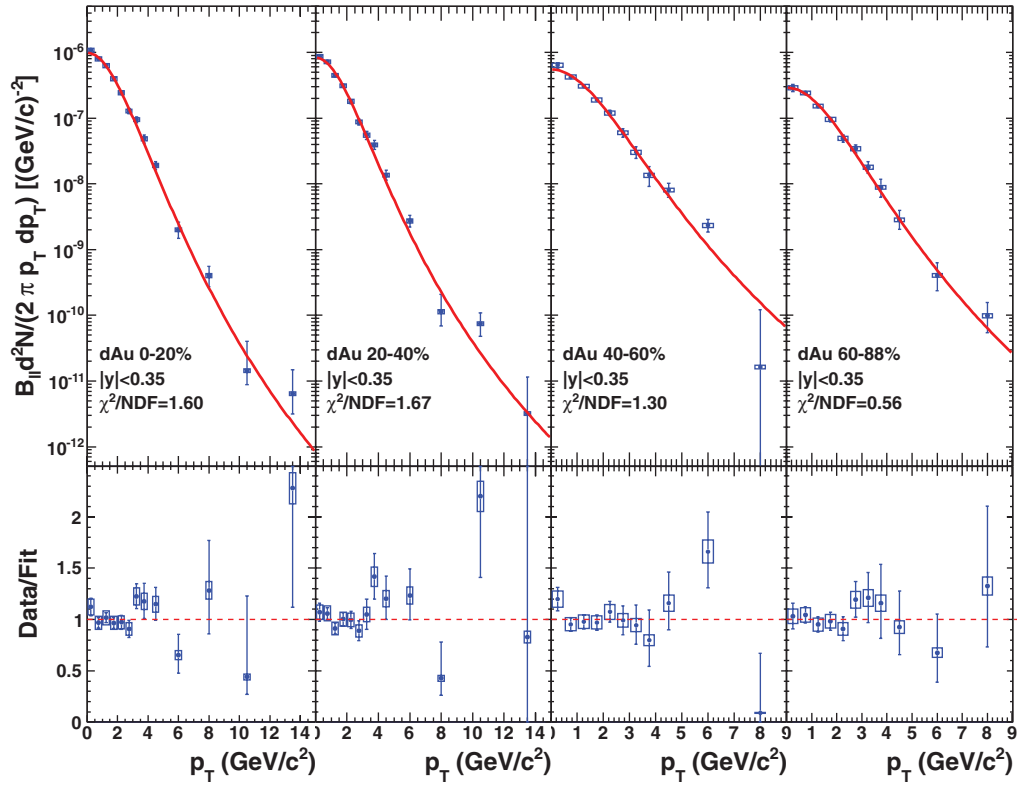
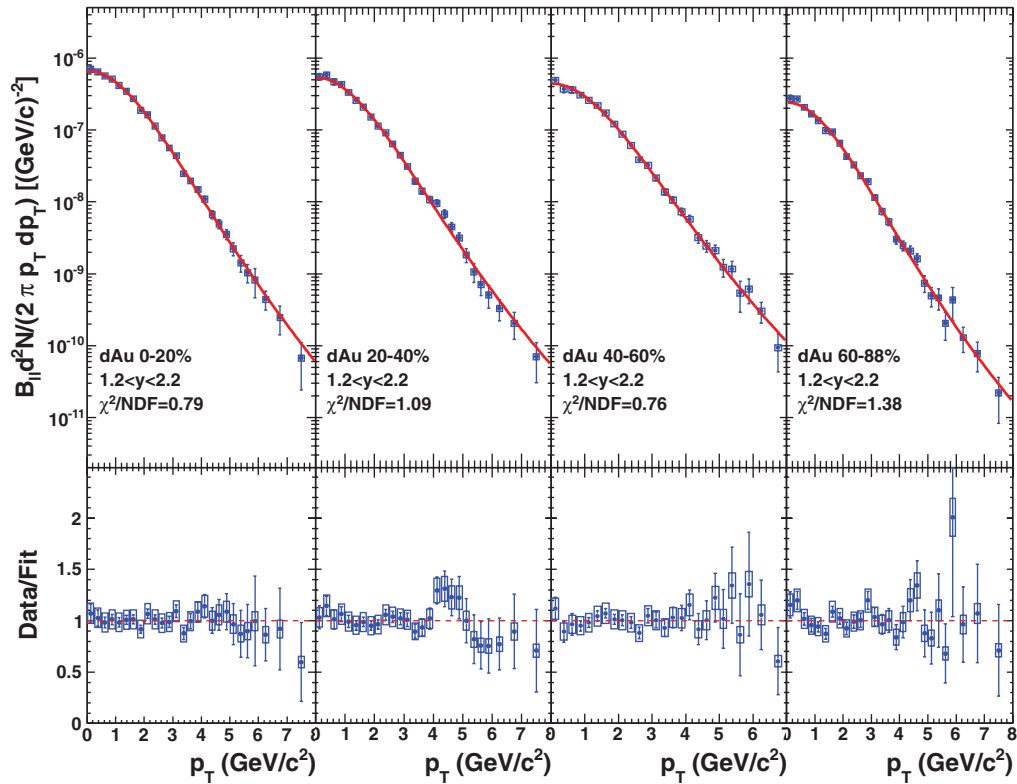
FIG. 18. (Color online) Results of modified Kaplan fits to midrapidity $d + \text{Au}$ collisions for each centrality.FIG. 19. (Color online) Results of modified Kaplan fits to forward-rapidity $d + \text{Au}$ collisions for each centrality.

TABLE VI. $\langle p_T^2 \rangle$ correction factors, k , for $p + p$ and $d + \text{Au}$ collisions.

System	y range	Centrality (%)	k
$p + p$	$1.2 < y < 2.2$		1.006 ± 0.001
$p + p$	$ y < 0.35$		1.018 ± 0.007
$d + \text{Au}$	$-2.2 < y < -1.2$	0–100	1.005 ± 0.001
$d + \text{Au}$	$ y < 0.35$	0–100	1.002 ± 0.001
$d + \text{Au}$	$1.2 < y < 2.2$	0–100	1.010 ± 0.002
$d + \text{Au}$	$-2.2 < y < -1.2$	0–20	1.005 ± 0.002
$d + \text{Au}$	$-2.2 < y < -1.2$	20–40	1.002 ± 0.001
$d + \text{Au}$	$-2.2 < y < -1.2$	40–60	1.006 ± 0.002
$d + \text{Au}$	$-2.2 < y < -1.2$	60–88	1.008 ± 0.003
$d + \text{Au}$	$ y < 0.35$	0–20	1.001 ± 0.001
$d + \text{Au}$	$ y < 0.35$	20–40	1.002 ± 0.002
$d + \text{Au}$	$ y < 0.35$	40–60	1.024 ± 0.017
$d + \text{Au}$	$ y < 0.35$	60–88	1.020 ± 0.024
$d + \text{Au}$	$1.2 < y < 2.2$	0–20	1.009 ± 0.003
$d + \text{Au}$	$1.2 < y < 2.2$	20–40	1.012 ± 0.003
$d + \text{Au}$	$1.2 < y < 2.2$	40–60	1.023 ± 0.006
$d + \text{Au}$	$1.2 < y < 2.2$	60–88	1.010 ± 0.004

APPENDIX B: DATA TABLES

The numerical values of 0–100% centrality-integrated $R_{d\text{Au}}$ vs p_T are given in Tables VII, VIII, and IX for backward, mid,

TABLE VIII. Data tables for 0–100% centrality-integrated $R_{d\text{Au}}$ in the interval $|y| < 0.35$.

p_T (GeV/c)	$R_{d\text{Au}}$	Type A	Type B	Type C
0.0–0.5	0.78	± 0.065	± 0.11	± 0.061
0.5–1.0	0.69	± 0.036	± 0.094	± 0.055
1.0–1.5	0.68	± 0.035	± 0.092	± 0.053
1.5–2.0	0.78	± 0.048	± 0.1	± 0.061
2.0–2.5	0.90	± 0.076	± 0.12	± 0.071
2.5–3.0	0.84	± 0.092	± 0.11	± 0.066
3.0–3.5	1.00	± 0.14	± 0.13	± 0.078
3.5–4.0	1.10	± 0.21	± 0.15	± 0.087
4.0–5.0	1.10	$^{+0.22}_{-0.21}$	± 0.14	± 0.084
5.0–7.0	0.91	± 0.21	$^{+0.11}_{-0.13}$	± 0.072
7.0–9.0	0.77	$^{+0.4}_{-0.34}$	$^{+0.09}_{-0.12}$	± 0.06

and forward rapidity, respectively. The numerical values of $R_{d\text{Au}}$ vs p_T for backward, mid, and forward rapidity are given in Tables X, XI, XII, and XIII for 0–20%, 20–40%, 40–60%, and 60–88% central collisions, respectively.

TABLE VII. Data tables for 0–100% centrality-integrated $R_{d\text{Au}}$ in the interval $-2.2 < y < -1.2$.

p_T (GeV/c)	$R_{d\text{Au}}$	Type A	Type B	Type C
0.00–0.25	0.759	± 0.1	± 0.053	± 0.063
0.25–0.50	0.772	± 0.094	± 0.054	± 0.064
0.50–0.75	0.853	± 0.092	± 0.059	± 0.071
0.75–1.00	0.899	± 0.06	± 0.062	± 0.074
1.00–1.25	0.955	± 0.048	± 0.065	± 0.079
1.25–1.50	0.934	± 0.048	± 0.064	± 0.077
1.50–1.75	0.988	± 0.048	± 0.068	± 0.082
1.75–2.00	1.000	± 0.049	± 0.069	± 0.083
2.00–2.25	1.043	± 0.054	± 0.072	± 0.086
2.25–2.50	1.182	± 0.061	± 0.081	± 0.098
2.50–2.75	1.159	± 0.059	± 0.08	± 0.096
2.75–3.00	1.161	± 0.067	± 0.08	± 0.096
3.00–3.25	1.150	± 0.075	± 0.079	± 0.095
3.25–3.50	1.059	± 0.076	± 0.073	± 0.088
3.50–3.75	1.234	± 0.101	± 0.085	± 0.102
3.75–4.00	1.043	± 0.098	± 0.072	± 0.086
4.00–4.25	1.285	± 0.15	± 0.089	± 0.106
4.25–4.50	1.133	± 0.152	± 0.078	± 0.094
4.50–4.75	1.556	± 0.252	± 0.108	± 0.129
4.75–5.00	1.265	± 0.256	± 0.089	± 0.105
5.00–5.50	1.186	± 0.303	± 0.083	± 0.098
5.50–6.00	1.227	± 0.518	± 0.085	± 0.101
6.00–7.00	1.228	± 0.537	± 0.085	± 0.102
7.00–8.00	1.643	± 1.036	± 0.116	± 0.136

TABLE IX. Data tables for 0–100% centrality-integrated $R_{d\text{Au}}$ in the interval $1.2 < y < 2.2$.

p_T (GeV/c)	$R_{d\text{Au}}$	Type A	Type B	Type C
0.00–0.25	0.693	± 0.064	± 0.052	± 0.057
0.25–0.50	0.690	± 0.059	± 0.052	± 0.057
0.50–0.75	0.664	± 0.048	$\pm 0.05\%$	± 0.055
0.75–1.00	0.659	± 0.037	± 0.049	± 0.054
1.00–1.25	0.652	± 0.032	± 0.048	± 0.054
1.25–1.50	0.671	± 0.032	$\pm 0.05\%$	± 0.055
1.50–1.75	0.739	± 0.029	± 0.055	± 0.061
1.75–2.00	0.703	± 0.029	± 0.052	± 0.058
2.00–2.25	0.732	± 0.031	± 0.054	± 0.061
2.25–2.50	0.772	± 0.035	± 0.057	± 0.064
2.50–2.75	0.764	± 0.037	± 0.057	± 0.063
2.75–3.00	0.821	± 0.043	± 0.061	± 0.068
3.00–3.25	0.844	± 0.049	± 0.063	$\pm 0.07\%$
3.25–3.50	0.716	± 0.048	± 0.053	± 0.059
3.50–3.75	0.765	± 0.056	± 0.057	± 0.063
3.75–4.00	0.786	$\pm 0.07\%$	± 0.059	± 0.065
4.00–4.25	1.032	± 0.107	± 0.077	± 0.085
4.25–4.50	1.030	± 0.129	± 0.077	± 0.085
4.50–4.75	1.118	± 0.166	± 0.084	± 0.092
4.75–5.00	1.047	± 0.186	± 0.079	± 0.087
5.00–5.50	0.836	± 0.195	± 0.063	± 0.069
5.50–6.00	0.984	± 0.298	± 0.074	± 0.081
6.00–7.00	1.122	± 0.387	± 0.084	± 0.093
7.00–8.00	1.275	$\pm 0.83\%$	± 0.097	± 0.105

TABLE X. Data tables for R_{dAu} as a function of p_T for 0–20% centrality.

y	p_T (GeV/ c)	R_{dAu}	Type A	Type B	Type C
$-2.2 < y < -1.2$	0.00–0.25	0.702	± 0.121	± 0.049	± 0.063
$-2.2 < y < -1.2$	0.25–0.50	0.760	± 0.104	± 0.053	± 0.068
$-2.2 < y < -1.2$	0.50–0.75	0.840	± 0.105	± 0.058	± 0.075
$-2.2 < y < -1.2$	0.75–1.00	0.894	± 0.076	± 0.062	± 0.08
$-2.2 < y < -1.2$	1.00–1.25	0.954	± 0.059	± 0.065	± 0.085
$-2.2 < y < -1.2$	1.25–1.50	1.008	± 0.066	± 0.069	± 0.09
$-2.2 < y < -1.2$	1.50–1.75	1.000	± 0.061	± 0.069	± 0.089
$-2.2 < y < -1.2$	1.75–2.00	1.058	± 0.066	± 0.073	± 0.095
$-2.2 < y < -1.2$	2.00–2.25	1.058	± 0.062	± 0.073	± 0.095
$-2.2 < y < -1.2$	2.25–2.50	1.252	± 0.072	± 0.086	± 0.112
$-2.2 < y < -1.2$	2.50–2.75	1.240	± 0.076	± 0.085	± 0.111
$-2.2 < y < -1.2$	2.75–3.00	1.249	± 0.083	± 0.086	± 0.112
$-2.2 < y < -1.2$	3.00–3.25	1.230	± 0.095	± 0.085	± 0.11
$-2.2 < y < -1.2$	3.25–3.50	1.088	± 0.093	± 0.075	± 0.097
$-2.2 < y < -1.2$	3.50–3.75	1.406	± 0.13	± 0.097	± 0.126
$-2.2 < y < -1.2$	3.75–4.00	1.131	± 0.124	± 0.078	± 0.101
$-2.2 < y < -1.2$	4.00–4.25	1.244	± 0.165	± 0.086	± 0.111
$-2.2 < y < -1.2$	4.25–4.50	1.209	± 0.186	± 0.084	± 0.108
$-2.2 < y < -1.2$	4.50–4.75	1.824	± 0.314	± 0.127	± 0.163
$-2.2 < y < -1.2$	4.75–5.00	1.508	± 0.329	± 0.106	± 0.135
$-2.2 < y < -1.2$	5.00–5.50	1.182	± 0.33	± 0.082	± 0.106
$-2.2 < y < -1.2$	5.50–6.00	1.171	± 0.522	± 0.082	± 0.105
$-2.2 < y < -1.2$	6.00–7.00	1.848	± 0.83	± 0.128	± 0.165
$-2.2 < y < -1.2$	7.00–8.00	2.079	± 1.364	± 0.146	± 0.186
$ y < 0.35$	0.0–0.5	0.69	± 0.071	± 0.094	± 0.059
$ y < 0.35$	0.5–1.0	0.60	± 0.04	± 0.081	± 0.051
$ y < 0.35$	1.0–1.5	0.65	± 0.042	± 0.088	± 0.056
$ y < 0.35$	1.5–2.0	0.73	± 0.054	± 0.097	± 0.062
$ y < 0.35$	2.0–2.5	0.88	± 0.088	± 0.12	± 0.075
$ y < 0.35$	2.5–2.0	0.81	± 0.11	± 0.11	± 0.07
$ y < 0.35$	2.0–3.5	1.10	± 0.17	± 0.15	± 0.096
$ y < 0.35$	3.5–4.0	1.10	$^{+0.25}_{-0.24}$	± 0.15	± 0.098
$ y < 0.35$	4.0–5.0	1.10	$^{+0.26}_{-0.24}$	± 0.15	± 0.095
$ y < 0.35$	5.0–7.0	0.59	$^{+0.21}_{-0.19}$	$^{+0.073}_{-0.087}$	± 0.051
$ y < 0.35$	7.0–9.0	1.10	$^{+0.61}_{-0.54}$	$^{+0.13}_{-0.17}$	± 0.095
$1.2 < y < 2.2$	0.00–0.25	0.566	± 0.054	± 0.042	± 0.051
$1.2 < y < 2.2$	0.25–0.50	0.557	± 0.046	± 0.042	± 0.05
$1.2 < y < 2.2$	0.50–0.75	0.557	± 0.034	± 0.042	± 0.05
$1.2 < y < 2.2$	0.75–1.00	0.563	± 0.031	± 0.042	± 0.05
$1.2 < y < 2.2$	1.00–1.25	0.559	± 0.029	± 0.042	± 0.05
$1.2 < y < 2.2$	1.25–1.50	0.594	± 0.029	± 0.044	± 0.053
$1.2 < y < 2.2$	1.50–1.75	0.634	± 0.031	± 0.047	± 0.057
$1.2 < y < 2.2$	1.75–2.00	0.587	± 0.029	± 0.044	± 0.052
$1.2 < y < 2.2$	2.00–2.25	0.698	± 0.034	± 0.052	± 0.062
$1.2 < y < 2.2$	2.25–2.50	0.691	± 0.037	± 0.051	± 0.062
$1.2 < y < 2.2$	2.50–2.75	0.691	± 0.041	± 0.052	± 0.062
$1.2 < y < 2.2$	2.75–3.00	0.713	± 0.047	± 0.053	± 0.064
$1.2 < y < 2.2$	3.00–3.25	0.812	± 0.056	± 0.061	± 0.073
$1.2 < y < 2.2$	3.25–3.50	0.631	± 0.052	± 0.047	± 0.056
$1.2 < y < 2.2$	3.50–3.75	0.708	± 0.064	± 0.053	± 0.063
$1.2 < y < 2.2$	3.75–4.00	0.772	± 0.081	± 0.058	± 0.069
$1.2 < y < 2.2$	4.00–4.25	0.922	± 0.112	± 0.069	± 0.083
$1.2 < y < 2.2$	4.25–4.50	0.834	± 0.124	± 0.062	± 0.075
$1.2 < y < 2.2$	4.50–4.75	0.953	± 0.163	± 0.071	± 0.085
$1.2 < y < 2.2$	4.75–5.00	0.922	± 0.183	± 0.07	± 0.082
$1.2 < y < 2.2$	5.00–5.50	0.735	± 0.192	± 0.055	± 0.066
$1.2 < y < 2.2$	5.50–6.00	0.997	± 0.396	± 0.075	± 0.089
$1.2 < y < 2.2$	6.00–7.00	0.971	± 0.378	± 0.073	± 0.087
$1.2 < y < 2.2$	7.00–8.00	0.989	± 0.739	± 0.075	± 0.089

TABLE XI. Data tables for R_{dAu} as a function of p_T for 20–40% centrality.

y	p_T (GeV/ c)	R_{dAu}	Type A	Type B	Type C
$-2.2 < y < -1.2$	0.00–0.25	0.706	± 0.123	± 0.049	± 0.06
$-2.2 < y < -1.2$	0.25–0.50	0.739	± 0.108	± 0.052	± 0.063
$-2.2 < y < -1.2$	0.50–0.75	0.815	± 0.113	± 0.057	± 0.07
$-2.2 < y < -1.2$	0.75–1.00	0.925	± 0.069	± 0.064	± 0.079
$-2.2 < y < -1.2$	1.00–1.25	0.984	± 0.051	± 0.068	± 0.084
$-2.2 < y < -1.2$	1.25–1.50	0.874	± 0.059	± 0.06	± 0.075
$-2.2 < y < -1.2$	1.50–1.75	1.021	± 0.054	± 0.07	± 0.087
$-2.2 < y < -1.2$	1.75–2.00	1.008	± 0.054	± 0.069	± 0.086
$-2.2 < y < -1.2$	2.00–2.25	1.067	± 0.06	± 0.073	± 0.091
$-2.2 < y < -1.2$	2.25–2.50	1.169	± 0.072	± 0.08	± 0.1
$-2.2 < y < -1.2$	2.50–2.75	1.103	± 0.073	± 0.076	± 0.094
$-2.2 < y < -1.2$	2.75–3.00	1.137	± 0.084	± 0.078	± 0.097
$-2.2 < y < -1.2$	3.00–3.25	1.160	± 0.101	± 0.08	± 0.099
$-2.2 < y < -1.2$	3.25–3.50	1.099	± 0.102	± 0.076	± 0.094
$-2.2 < y < -1.2$	3.50–3.75	1.234	± 0.131	± 0.085	± 0.106
$-2.2 < y < -1.2$	3.75–4.00	0.957	± 0.121	± 0.066	± 0.082
$-2.2 < y < -1.2$	4.00–4.25	1.376	± 0.195	± 0.095	± 0.118
$-2.2 < y < -1.2$	4.25–4.50	1.077	± 0.19	± 0.075	± 0.092
$-2.2 < y < -1.2$	4.50–4.75	1.401	± 0.28	± 0.097	± 0.12
$-2.2 < y < -1.2$	4.75–5.00	1.028	± 0.266	± 0.072	± 0.088
$-2.2 < y < -1.2$	5.00–5.50	1.481	± 0.496	± 0.103	± 0.127
$-2.2 < y < -1.2$	5.50–6.00	1.188	± 0.641	± 0.083	± 0.102
$-2.2 < y < -1.2$	6.00–7.00	0.793	± 0.469	± 0.055	± 0.068
$-2.2 < y < -1.2$	7.00–8.00	0.996	± 0.836	± 0.07	± 0.085
$ y < 0.35$	0.0–0.5	0.83	± 0.089	± 0.11	± 0.068
$ y < 0.35$	0.5–1.0	0.80	± 0.055	± 0.11	± 0.065
$ y < 0.35$	1.0–1.5	0.69	± 0.05	± 0.093	± 0.056
$ y < 0.35$	1.5–2.0	0.85	± 0.069	± 0.11	± 0.069
$ y < 0.35$	2.0–2.5	0.97	± 0.11	± 0.13	± 0.079
$ y < 0.35$	2.5–2.0	0.82	± 0.12	± 0.11	± 0.067
$ y < 0.35$	2.0–3.5	0.97	± 0.18	± 0.13	± 0.079
$ y < 0.35$	3.5–4.0	1.40	± 0.31	± 0.18	± 0.11
$ y < 0.35$	4.0–5.0	1.20	$^{+0.3}_{-0.28}$	± 0.16	± 0.096
$ y < 0.35$	5.0–7.0	1.20	$^{+0.33}_{-0.32}$	$^{+0.15}_{-0.18}$	± 0.098
$ y < 0.35$	7.0–9.0	0.47	$^{+0.43}_{-0.25}$	$^{+0.054}_{-0.071}$	± 0.038
$1.2 < y < 2.2$	0.00–0.25	0.649	± 0.076	± 0.049	± 0.056
$1.2 < y < 2.2$	0.25–0.50	0.735	± 0.066	± 0.056	± 0.063
$1.2 < y < 2.2$	0.50–0.75	0.680	± 0.065	± 0.051	± 0.058
$1.2 < y < 2.2$	0.75–1.00	0.697	± 0.05	± 0.052	± 0.06
$1.2 < y < 2.2$	1.00–1.25	0.661	± 0.042	± 0.049	± 0.057
$1.2 < y < 2.2$	1.25–1.50	0.653	± 0.035	± 0.048	± 0.056
$1.2 < y < 2.2$	1.50–1.75	0.712	± 0.037	± 0.053	± 0.061
$1.2 < y < 2.2$	1.75–2.00	0.701	± 0.037	± 0.052	± 0.06
$1.2 < y < 2.2$	2.00–2.25	0.716	± 0.039	± 0.053	± 0.061
$1.2 < y < 2.2$	2.25–2.50	0.818	± 0.047	± 0.061	± 0.07
$1.2 < y < 2.2$	2.50–2.75	0.831	± 0.052	± 0.062	± 0.071
$1.2 < y < 2.2$	2.75–3.00	0.831	± 0.057	± 0.062	± 0.071
$1.2 < y < 2.2$	3.00–3.25	0.844	± 0.065	± 0.063	± 0.072
$1.2 < y < 2.2$	3.25–3.50	0.728	± 0.066	± 0.054	± 0.062
$1.2 < y < 2.2$	3.50–3.75	0.752	± 0.075	± 0.056	± 0.064
$1.2 < y < 2.2$	3.75–4.00	0.819	± 0.095	± 0.061	± 0.07
$1.2 < y < 2.2$	4.00–4.25	1.191	± 0.148	± 0.089	± 0.102
$1.2 < y < 2.2$	4.25–4.50	1.252	± 0.192	± 0.094	± 0.107
$1.2 < y < 2.2$	4.50–4.75	1.276	± 0.223	± 0.096	± 0.109
$1.2 < y < 2.2$	4.75–5.00	1.206	± 0.247	± 0.091	± 0.103
$1.2 < y < 2.2$	5.00–5.50	0.859	± 0.237	± 0.065	± 0.074
$1.2 < y < 2.2$	5.50–6.00	0.960	± 0.356	± 0.072	± 0.082
$1.2 < y < 2.2$	6.00–7.00	1.111	± 0.448	± 0.083	± 0.095
$1.2 < y < 2.2$	7.00–8.00	1.519	± 1.038	± 0.115	± 0.13

TABLE XII. Data tables for R_{dAu} as a function of p_T for 40–60% centrality.

y	p_T (GeV/c)	R_{dAu}	Type A	Type B	Type C
$-2.2 < y < -1.2$	0.00–0.25	0.953	± 0.103	± 0.066	± 0.087
$-2.2 < y < -1.2$	0.25–0.50	0.865	± 0.104	± 0.061	± 0.079
$-2.2 < y < -1.2$	0.50–0.75	0.995	± 0.094	± 0.069	± 0.09
$-2.2 < y < -1.2$	0.75–1.00	0.920	± 0.06	± 0.063	± 0.084
$-2.2 < y < -1.2$	1.00–1.25	0.976	± 0.055	± 0.067	± 0.089
$-2.2 < y < -1.2$	1.25–1.50	0.929	± 0.056	± 0.064	± 0.084
$-2.2 < y < -1.2$	1.50–1.75	0.979	± 0.067	± 0.067	± 0.089
$-2.2 < y < -1.2$	1.75–2.00	1.018	± 0.06	± 0.07	± 0.093
$-2.2 < y < -1.2$	2.00–2.25	1.015	± 0.074	± 0.07	± 0.092
$-2.2 < y < -1.2$	2.25–2.50	1.159	± 0.091	± 0.08	± 0.105
$-2.2 < y < -1.2$	2.50–2.75	1.227	± 0.086	± 0.085	± 0.112
$-2.2 < y < -1.2$	2.75–3.00	1.036	± 0.088	± 0.071	± 0.094
$-2.2 < y < -1.2$	3.00–3.25	1.046	± 0.101	± 0.072	± 0.095
$-2.2 < y < -1.2$	3.25–3.50	1.114	± 0.114	± 0.077	± 0.101
$-2.2 < y < -1.2$	3.50–3.75	1.152	± 0.14	± 0.08	± 0.105
$-2.2 < y < -1.2$	3.75–4.00	1.124	± 0.153	± 0.078	± 0.102
$-2.2 < y < -1.2$	4.00–4.25	1.313	± 0.212	± 0.091	± 0.119
$-2.2 < y < -1.2$	4.25–4.50	1.427	± 0.253	± 0.099	± 0.13
$-2.2 < y < -1.2$	4.50–4.75	1.080	± 0.263	± 0.075	± 0.098
$-2.2 < y < -1.2$	4.75–5.00	1.365	± 0.356	± 0.096	± 0.124
$-2.2 < y < -1.2$	5.00–5.50	0.985	± 0.345	± 0.069	± 0.09
$-2.2 < y < -1.2$	5.50–6.00	1.354	± 0.796	± 0.094	± 0.123
$-2.2 < y < -1.2$	6.00–7.00	1.297	± 0.671	± 0.09	± 0.118
$-2.2 < y < -1.2$	7.00–8.00	4.130	± 2.905	± 0.291	± 0.375
$ y < 0.35$	0.0–0.5	0.94	± 0.11	± 0.13	± 0.082
$ y < 0.35$	0.5–1.0	0.73	± 0.059	± 0.098	± 0.063
$ y < 0.35$	1.0–1.5	0.73	± 0.059	± 0.099	± 0.064
$ y < 0.35$	1.5–2.0	0.80	± 0.074	± 0.11	± 0.07
$ y < 0.35$	2.0–2.5	0.99	± 0.12	± 0.14	± 0.087
$ y < 0.35$	2.5–2.0	0.87	± 0.15	± 0.12	± 0.076
$ y < 0.35$	2.0–3.5	0.82	$^{+0.2}_{-0.19}$	± 0.11	± 0.072
$ y < 0.35$	3.5–4.0	0.73	$^{+0.29}_{-0.26}$	± 0.098	± 0.064
$ y < 0.35$	4.0–5.0	1.10	$^{+0.34}_{-0.3}$	± 0.14	± 0.094
$ y < 0.35$	5.0–7.0	1.60	$^{+0.47}_{-0.45}$	$^{+0.2}_{-0.23}$	± 0.14
$ y < 0.35$	7.0–9.0	0.10	$^{+0.67}_{-0.51}$	± 0.012	± 0.009
$1.2 < y < 2.2$	0.00–0.25	0.897	± 0.098	± 0.067	± 0.082
$1.2 < y < 2.2$	0.25–0.50	0.731	± 0.087	± 0.055	± 0.067
$1.2 < y < 2.2$	0.50–0.75	0.816	± 0.093	± 0.061	± 0.074
$1.2 < y < 2.2$	0.75–1.00	0.778	± 0.046	± 0.058	± 0.071
$1.2 < y < 2.2$	1.00–1.25	0.802	± 0.042	± 0.06	± 0.073
$1.2 < y < 2.2$	1.25–1.50	0.862	± 0.046	± 0.064	± 0.078
$1.2 < y < 2.2$	1.50–1.75	0.916	± 0.045	± 0.068	± 0.083
$1.2 < y < 2.2$	1.75–2.00	0.865	± 0.047	± 0.064	± 0.079
$1.2 < y < 2.2$	2.00–2.25	0.859	± 0.051	± 0.064	± 0.078
$1.2 < y < 2.2$	2.25–2.50	0.854	± 0.056	± 0.064	± 0.078
$1.2 < y < 2.2$	2.50–2.75	0.781	± 0.057	± 0.058	± 0.071
$1.2 < y < 2.2$	2.75–3.00	0.933	± 0.072	± 0.069	± 0.085
$1.2 < y < 2.2$	3.00–3.25	0.907	± 0.079	± 0.068	± 0.082
$1.2 < y < 2.2$	3.25–3.50	0.807	± 0.081	± 0.06	± 0.073
$1.2 < y < 2.2$	3.50–3.75	0.878	± 0.096	± 0.066	± 0.08
$1.2 < y < 2.2$	3.75–4.00	0.868	± 0.115	± 0.065	± 0.079
$1.2 < y < 2.2$	4.00–4.25	1.109	± 0.161	± 0.083	± 0.101
$1.2 < y < 2.2$	4.25–4.50	0.911	± 0.167	± 0.068	± 0.083
$1.2 < y < 2.2$	4.50–4.75	1.082	± 0.23	± 0.081	± 0.098
$1.2 < y < 2.2$	4.75–5.00	1.246	± 0.281	± 0.094	± 0.113
$1.2 < y < 2.2$	5.00–5.50	1.114	± 0.343	± 0.084	± 0.101
$1.2 < y < 2.2$	5.50–6.00	1.417	± 0.632	± 0.107	± 0.129
$1.2 < y < 2.2$	6.00–7.00	1.268	± 0.55	± 0.095	± 0.115
$1.2 < y < 2.2$	7.00–8.00	0.747	$\pm 7.473\text{e}+39$	± 0.057	± 0.068

TABLE XIII. Data tables for R_{dAu} as a function of p_T for 60–88% centrality.

y	p_T (GeV/c)	R_{dAu}	Type A	Type B	Type C
$-2.2 < y < -1.2$	0.00–0.25	0.829	± 0.14	± 0.057	± 0.088
$-2.2 < y < -1.2$	0.25–0.50	0.823	± 0.091	± 0.058	± 0.088
$-2.2 < y < -1.2$	0.50–0.75	0.922	± 0.074	± 0.064	± 0.098
$-2.2 < y < -1.2$	0.75–1.00	0.965	± 0.068	± 0.066	± 0.103
$-2.2 < y < -1.2$	1.00–1.25	0.947	± 0.057	± 0.065	± 0.101
$-2.2 < y < -1.2$	1.25–1.50	0.965	± 0.059	± 0.066	± 0.103
$-2.2 < y < -1.2$	1.50–1.75	0.990	± 0.058	± 0.068	± 0.105
$-2.2 < y < -1.2$	1.75–2.00	0.888	± 0.059	± 0.061	± 0.095
$-2.2 < y < -1.2$	2.00–2.25	1.097	± 0.077	± 0.075	± 0.117
$-2.2 < y < -1.2$	2.25–2.50	1.073	± 0.084	± 0.074	± 0.114
$-2.2 < y < -1.2$	2.50–2.75	1.047	± 0.09	± 0.072	± 0.111
$-2.2 < y < -1.2$	2.75–3.00	1.175	± 0.107	± 0.081	± 0.125
$-2.2 < y < -1.2$	3.00–3.25	1.132	± 0.122	± 0.078	± 0.12
$-2.2 < y < -1.2$	3.25–3.50	0.908	± 0.115	± 0.063	± 0.097
$-2.2 < y < -1.2$	3.50–3.75	0.926	± 0.138	± 0.064	± 0.099
$-2.2 < y < -1.2$	3.75–4.00	0.804	± 0.136	± 0.056	± 0.086
$-2.2 < y < -1.2$	4.00–4.25	1.277	± 0.234	± 0.088	± 0.136
$-2.2 < y < -1.2$	4.25–4.50	0.642	± 0.187	± 0.044	± 0.068
$-2.2 < y < -1.2$	4.50–4.75	1.827	± 0.401	± 0.127	± 0.194
$-2.2 < y < -1.2$	4.75–5.00	0.700	± 0.251	± 0.049	± 0.075
$-2.2 < y < -1.2$	5.00–5.50	1.193	± 0.42	± 0.083	± 0.127
$-2.2 < y < -1.2$	5.50–6.00	3.141	± 1.737	± 0.219	± 0.334
$-2.2 < y < -1.2$	6.00–7.00	1.122	± 0.714	± 0.078	± 0.119
$-2.2 < y < -1.2$	7.00–8.00	0.443	$\pm 4.427\text{e}+39$	± 0.031	± 0.047
$ y < 0.35$	0.0–0.5	0.91	± 0.13	± 0.12	± 0.094
$ y < 0.35$	0.5–1.0	0.88	± 0.077	± 0.12	± 0.091
$ y < 0.35$	1.0–1.5	0.77	± 0.069	± 0.1	± 0.08
$ y < 0.35$	1.5–2.0	0.86	± 0.089	± 0.11	± 0.089
$ y < 0.35$	2.0–2.5	0.87	± 0.13	± 0.12	± 0.09
$ y < 0.35$	2.5–2.0	1.10	± 0.18	± 0.14	± 0.11
$ y < 0.35$	2.0–3.5	1.00	± 0.24	± 0.14	± 0.11
$ y < 0.35$	3.5–4.0	1.00	$^{+0.37}_{-0.35}$	± 0.14	± 0.11
$ y < 0.35$	4.0–5.0	0.81	$^{+0.34}_{-0.27}$	± 0.11	± 0.084
$ y < 0.35$	5.0–7.0	0.59	$^{+0.34}_{-0.27}$	$^{+0.073}_{-0.086}$	± 0.061
$ y < 0.35$	7.0–9.0	1.30	$^{+0.94}_{-0.75}$	$^{+0.15}_{-0.2}$	± 0.14
$1.2 < y < 2.2$	0.00–0.25	1.038	± 0.123	± 0.078	± 0.111
$1.2 < y < 2.2$	0.25–0.50	1.100	± 0.089	± 0.083	± 0.117
$1.2 < y < 2.2$	0.50–0.75	0.961	± 0.064	± 0.072	± 0.102
$1.2 < y < 2.2$	0.75–1.00	0.873	± 0.065	± 0.065	± 0.093
$1.2 < y < 2.2$	1.00–1.25	0.859	± 0.05	± 0.064	± 0.091
$1.2 < y < 2.2$	1.25–1.50	0.800	± 0.051	± 0.059	± 0.085
$1.2 < y < 2.2$	1.50–1.75	1.028	± 0.054	± 0.076	± 0.109
$1.2 < y < 2.2$	1.75–2.00	0.963	± 0.058	± 0.072	± 0.103
$1.2 < y < 2.2$	2.00–2.25	0.864	± 0.062	± 0.064	± 0.092
$1.2 < y < 2.2$	2.25–2.50	0.939	± 0.068	± 0.07	± 0.1
$1.2 < y < 2.2$	2.50–2.75	0.966	± 0.076	± 0.072	± 0.103
$1.2 < y < 2.2$	2.75–3.00	1.146	± 0.094	± 0.085	± 0.122
$1.2 < y < 2.2$	3.00–3.25	0.999	± 0.097	± 0.075	± 0.106
$1.2 < y < 2.2$	3.25–3.50	0.886	± 0.097	± 0.066	± 0.094
$1.2 < y < 2.2$	3.50–3.75	0.897	± 0.112	± 0.067	± 0.096
$1.2 < y < 2.2$	3.75–4.00	0.741	± 0.116	± 0.055	± 0.079
$1.2 < y < 2.2$	4.00–4.25	0.985	± 0.169	± 0.074	± 0.105
$1.2 < y < 2.2$	4.25–4.50	1.228	± 0.227	± 0.092	± 0.131
$1.2 < y < 2.2$	4.50–4.75	1.477	± 0.305	± 0.111	± 0.157
$1.2 < y < 2.2$	4.75–5.00	0.906	± 0.257	± 0.068	± 0.096
$1.2 < y < 2.2$	5.00–5.50	0.913	± 0.309	± 0.069	± 0.097
$1.2 < y < 2.2$	5.50–6.00	1.622	± 0.816	± 0.122	± 0.173
$1.2 < y < 2.2$	6.00–7.00	1.381	± 0.628	± 0.103	± 0.147
$1.2 < y < 2.2$	7.00–8.00	1.527	± 1.12	± 0.116	± 0.163

- [1] N. Brambilla, S. Eidelman, B. Heltsley, R. Vogt, G. Bodwin *et al.*, *Eur. Phys. J. C* **71**, 1534 (2011).
- [2] J. Cronin, H. J. Frisch, M. Shochet, J. Boymond, R. Mermod *et al.*, *Phys. Rev. D* **11**, 3105 (1975).
- [3] M. Abreu *et al.* (NA38 Collaboration), *Phys. Lett. B* **444**, 516 (1998).
- [4] B. Alessandro *et al.* (NA50 Collaboration), *Phys. Lett. B* **553**, 167 (2003).
- [5] B. Alessandro *et al.* (NA50 Collaboration), *Eur. Phys. J. C* **33**, 31 (2004).
- [6] B. Alessandro *et al.* (NA50 Collaboration), *Eur. Phys. J. C* **48**, 329 (2006).
- [7] R. Arnaldi *et al.* (NA60 Collaboration), *Phys. Lett. B* **706**, 263 (2012).
- [8] M. J. Leitch *et al.* (FNAL E866/NuSea Collaboration), *Phys. Rev. Lett.* **84**, 3256 (2000).
- [9] I. Abt *et al.* (HERA-B Collaboration), *Eur. Phys. J. C* **60**, 525 (2009).
- [10] C. Lourenco, R. Vogt, and H. K. Woehri, *J. High Energy Phys.* **02** (2009) 014, and references therein.
- [11] T. Matsui and H. Satz, *Phys. Lett. B* **178**, 416 (1986).
- [12] R. Arnaldi *et al.* (NA60 Collaboration), *Phys. Rev. Lett.* **99**, 132302 (2007).
- [13] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **98**, 232301 (2007).
- [14] S. Chatrchyan *et al.* (CMS Collaboration), *J. High Energy Phys.* **05** (2012) 063.
- [15] B. Abelev *et al.* (ALICE Collaboration), *Phys. Rev. Lett.* **109**, 072301 (2012).
- [16] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. D* **85**, 092004 (2012).
- [17] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. C* **77**, 024912 (2008).
- [18] S. S. Adler *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **96**, 012304 (2006).
- [19] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **107**, 142301 (2011).
- [20] K. Adcox *et al.* (PHENIX Collaboration), *Nucl. Instrum. Methods A* **499**, 469 (2003).
- [21] S. N. White, *AIP Conf. Proc.* **792**, 527 (2005).
- [22] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, *Annu. Rev. Nucl. Part. Sci.* **57**, 205 (2007).
- [23] A. Spiridonov, [arXiv:hep-ex/0510076](https://arxiv.org/abs/hep-ex/0510076).
- [24] T. Sjostrand, S. Mrenna, and P. Z. Skands, *J. High Energy Phys.* **05** (2006) 026.
- [25] GEANT 3.2.1 Manual (CERN, Geneva, 1993); available at <http://wwwasdoc.web.cern.ch/wwwasdoc/pdfdir/geant.pdf>.
- [26] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.* **101**, 122301 (2008).
- [27] A. Adare *et al.* (PHENIX Collaboration), *Phys. Rev. C* **84**, 054912 (2011).
- [28] B. Abelev *et al.* (STAR Collaboration), *Phys. Rev. C* **80**, 041902 (2009).
- [29] E. G. Ferreira, F. Fleuret, J. P. Lansberg, N. Matagne, and A. Rakotozafindrabe, *Few Body Syst.* **53**, 27 (2012).
- [30] D. de Florian and R. Sassot, *Phys. Rev. D* **69**, 074028 (2004).
- [31] K. J. Eskola, V. J. Kolhinen, and C. A. Salgado, *Eur. Phys. J. C* **9**, 61 (1999).
- [32] K. J. Eskola, H. Paukkunen, and C. A. Salgado, *J. High Energy Phys.* **04** (2009) 065.
- [33] K. J. Golec-Biernat and M. Wusthoff, *Phys. Rev. D* **60**, 114023 (1999).
- [34] B. Kopeliovich, I. Potashnikova, and I. Schmidt, *Nucl. Phys. A* **864**, 203 (2011).
- [35] B. Z. Kopeliovich, I. K. Potashnikova, and I. Schmidt, *Phys. Rev. C* **82**, 024901 (2010).
- [36] J. L. Nagle, A. D. Frawley, L. A. Linden Levy, and M. G. Wysocki, *Phys. Rev. C* **84**, 044911 (2011).
- [37] E. Ferreira, F. Fleuret, J. Lansberg, and A. Rakotozafindrabe, *Phys. Lett. B* **680**, 50 (2009).
- [38] K. J. Eskola, H. Paukkunen, and C. A. Salgado, *J. High Energy Phys.* **07** (2008) 102.
- [39] J. Aubert *et al.* (European Muon Collaboration), *Phys. Lett. B* **123**, 275 (1983).
- [40] E. Ferreira, F. Fleuret, J. Lansberg, N. Matagne, and A. Rakotozafindrabe, [arXiv:1110.5047](https://arxiv.org/abs/1110.5047).
- [41] R. Sharma and I. Vitev, [arXiv:1203.0329](https://arxiv.org/abs/1203.0329).
- [42] I. Vitev, T. Goldman, M. B. Johnson, and J. W. Qiu, *Phys. Rev. D* **74**, 054010 (2006).